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ON FORECASTING THE DIRECTION OF MOVEMENT OF WINTER CYCLONES

Wayne C. Palmer

[U. S. Weather Bureau, Washington, D. C.]

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INTRODUCTION

THE PROBLEM

A need has long existed for a more systematic technique for quickly forecasting the location and intensity of cyclones. This need has been felt particularly at the Weather Bureau-Air Force-Navy Analysis Center, where prognostic pressure charts for wide areas must be prepared regularly, with a minimum time interval between collection of the data and dissemination of the finished charts.

Although it is well recognized that the direction of movement, the speed of movement, and the deepening and filling of cyclones are so interrelated as to constitute a single problem, the direction of movement during a 30-hour period was selected as the subject of the first investigation.[1] This selection was made because it seemed advisable to attack the various aspects of the problem individually in order to reduce the investigation to a reasonable scale, and the direction of movement seemed to be the simplest aspect and at the same time one of the most vital. A forecast of direction of cyclone movement during the next 30 hours is defined as the straight line extending from the current map position of an existing surface cyclone to the point at which the cyclone will be located 30 hours later—the line on which it will be found 30 hours later, regardless of the path it may follow or the distance it may travel during the period.

LIMITATIONS OF THE PRESENT STUDY

In order to secure data with some degree of homogeneity, the investigation was confined to cyclones found in the region of the United States and Canada east of the Continental Divide. Restrictions in season also seemed advisable, and therefore, only the winter months of December, January, and February were considered.

With attention to the operational problems of the WBAN Analysis Center, it was obvious that, to be useful, any technique developed must employ only those data which are available to the forecaster at the time he is preparing the prognostic chart; also, the technique must be sufficiently simple that a disproportionate amount of time will not be consumed in using it.

[1] A study designed to forecast the 30-hour deepening and filling of winter cyclones is in manuscript form and will be published later, and work is currently being done on the problem of forecasting the 30-hour speed of movement of winter cyclones.

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METHODS OF INVESTIGATION

A study such as this can be considered to comprise four distinct phases: first, selection of important factors related to the specific problem, based on previous theoretical studies and the experience of forecasters; second, measurement and numerical expression of those factors; third, determination from past data of their combined relationship to the item to be forecast; and fourth, verification of prognostications made by applying the developed technique to independent data. The second phase is the most difficult, although the value of the study depends on the outcome of the independent tests.

This investigation was not intended to discover new variables to be used in forecasting but, rather, to evaluate systematically some of the more important ones which are currently used or advocated. When a forecaster is deciding something about where a given low pressure center will be at some future time, he considers many aspects of current and past synoptic charts such as past movement, field of 3-hour isallobars, field of 12-hour pressure changes at sea level, general appearance of the current sea level pressure chart, flow patterns and changes at various upper levels, three-dimensional temperature field, and many others. In order to find the degree to which such aspects of the current meteorological situation are indicative of the subsequent 30-hour direction of movement of the low pressure center, a simple graphical procedure was employed in this study. A meteorological factor capable of numerical expression from available data was evaluated for a number of cases and then plotted against the ordinate of observed direction of movement of the low center during the following 30 hours. (Fig. 10 illustrates this procedure.) This method of investigation makes possible the establishment of relationships between the variable and the item to be forecast, without the necessity of first knowing the exact form of the relationship. If the data, when plotted on the graph, are found to be arranged in a systematic fashion, such as along and about a straight line or a curve, a relationship can be said to exist; if they are not arranged along some simple or slightly complex curve, it can only be concluded that any existing relationship is not evident from this simple method of handling the data. The variable under consideration must then be discarded, or some more precise means of expressing it must be found.

If it is suspected that two variables operate in a fashion demanding that they should be considered simultaneously, one can be used as the ordinate of a graph with the other as the abscissa, and the observed value of the item to be forecast (in this study, the observed direction of movement of the low center) can be entered at the intersection thus determined. (Fig. 14 illustrates this procedure.) When this type of graph includes a large number of cases, the values entered at the intersections can be analyzed for distribution and gradient; if some relationship exists, isopleths can be drawn. This simple device can be used advantageously on many problems when the exact forms of relationships are not known. To some extent, it takes care of the difficulty which frequently confronts a forecaster when consideration of two separate variables suggests differing forecasts. Sometimes the indications from one variable will be more nearly correct, sometimes the indications from the other. If the data are handled properly, this graphical technique will tend to give the proper weight to the various factors and thus help in resolving the forecaster's problem by indicating when one factor is more important than another.

The very simplicity of this approach may make it appear to the reader that a study such as this one is arbitrary, empirical, and superficial, This impression may be the result of the simple measures which are frequently used to express some aspect of a meteorological situation. For example, in a particular study it may be found, after rather exhaustive tests, that the surface dew point at some station is almost as good a measure of the amount of moisture in the air as more elaborate evaluations, such as total precipitable water in the atmospheric column or mean moisture content in some particular isentropic layer; then it is quite natural that the dew point will be used because it is so readily obtained. To the cursory reader the dew point at this particular station may seem to be of only minor importance in the solution of the problem at hand; but its use may be justified when closer examination shows that extreme values of dew point at that station will occur only with a certain synoptic situation, and that the dew point value is therefore a far more significant indicator than was first believed. Also, although it has often been found that more elaborate measures give somewhat better results, they may not be enough better to justify the additional difficulty and time involved in obtaining and resolving them into a unified forecasting tool.

INVESTIGATIONS

Of the 25 or 30 different factors which were investigated in the course of this study, 4 which seemed to contain nearly all of the useful information readily available from the current synoptic charts were:

1. A normal 24-hour direction of movement based on the data published by Bowie and Weightman [1].
2. The direction the particular cyclone moved during the past 6 hours.
3. The orientation of the major trough in the sea-level pressure pattern.
4. The direction from the 3-hour anallobaric center behind the cyclone to the 3-hour katallobaric center ahead of the cyclone.

A discussion of some of the other factors investigated will be found in the APPENDIX to this paper.

NORMAL DIRECTION OF MOVEMENT

When an experienced forecaster looks at a given weather situation and remarks that such a low generally moves "so and so," he is drawing upon the total of his experience with lows similar to the one in question. In a subjective way he has formed in his mind a "normal" path for such lows. There seems little doubt that this information is useful in forecasting; therefore, a quantitative evaluation of "normal" direction should be even more useful.

The work of Bowie and Weightman [1] gives, for each map area 5° square, the average 24-hour speed and direction of movement of lows for each month of the year. (No 30-hour averages were available.) These averages are based on 20 years of data and are grouped according to the geographical area (see fig. 1) in which the low first appeared and from which it received its type designation. Examination of the Bowie and Weightman data disclosed that the averages for some 5° squares were based on very few cases. For the purpose of the present study a more stable "normal" direction was needed. Inasmuch as the changes of the Bowie and Weightman average directions from month to month at any geographical point were considerably less than the changes of the averages from point to point, it was decided that representative "winter" normal directions by geographical type could be obtained by combining Bowie and Weightman data for the months of December, January, and February. This was done, with each month being weighted according to the number of cases of a particular type of cyclone recorded in the original observations for that month.

Figures 2 through 9 show the results of combining these winter data; the geographical types of the earlier investigation have been maintained separately, except for the South Atlantic and East Gulf types which were combined into a single normal chart because few data were available for either and differences between the types did not appear to be great. The average observed 24-hour direction of movement is shown by the numbers appearing on the maps in the center of each 5° square of figures 2 through 9; numbers in parentheses give the total number of "winter" cases which appear in that 5° square on the Bowie and Weightman maps. For example, in figure 4, the 5° square from 35° N. to 40° N. lat., and from 110° W. to 115° W. long., shows a direction of 0° for the average direction of movement of the 33 cases of South Pacific Lows. The 0° for direction of movement means a straight line tangent to the parallel of 37½° N. lat., at 112½° W. long., which in this case, therefore, passes approximately through Tulsa, Okla., and Savannah, Ga. (The error of measurement is negligible for directions laid off in this way on any conformal conic map projection, using an ordinary protractor oriented according to the meridians; however, a special direction-measuring device has to be used on other map projections.) The isograms on these maps were drawn and labeled in terms of degrees from "east" ("east" being 0° laid off as indicated above). Positive values indicate degrees north of east, and negative values show degrees south of east (with north as +90° and south as −90°). For example, an Alberta Low situated at Milwaukee, Wis., has an average 24-hour direction of movement of +15° (see fig. 2), which indicates a line approximately through Bangor, Maine.

In order to determine something of the usefulness of these modified Bowie and Weightman average directions, hereafter referred to as normal directions, 68 cases of winter cyclones east of the Continental Divide were

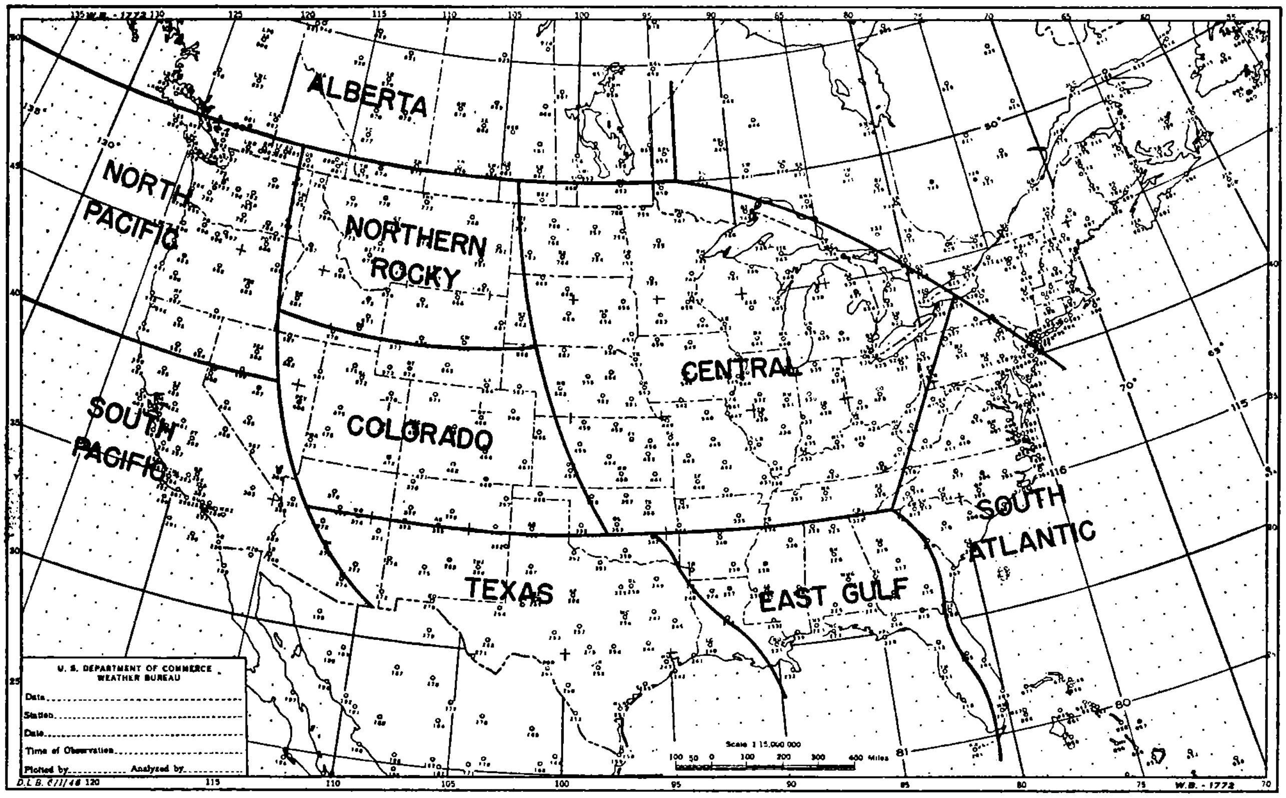

Figure 1.—Map showing regions of first appearance of storms on the weather map of the United States and Canada, used for designation of storm types. (From Bowie and Weightman [1]).

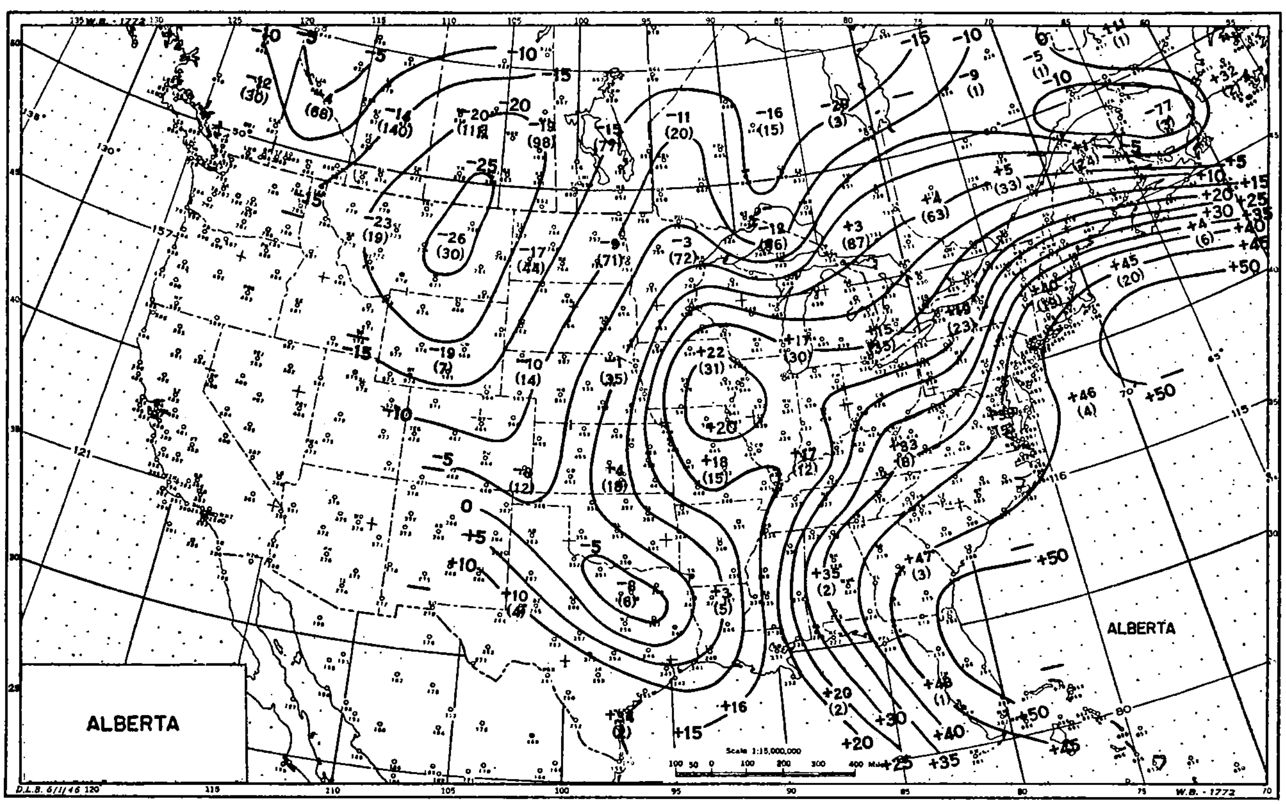

Figure 2.—Map showing isograms of average 24-hour direction of movement of winter cyclones, drawn from average direction of movement by 5° squares (shown by numbers), based on winter cases in Bowie and Weightman data (numbers in parentheses).

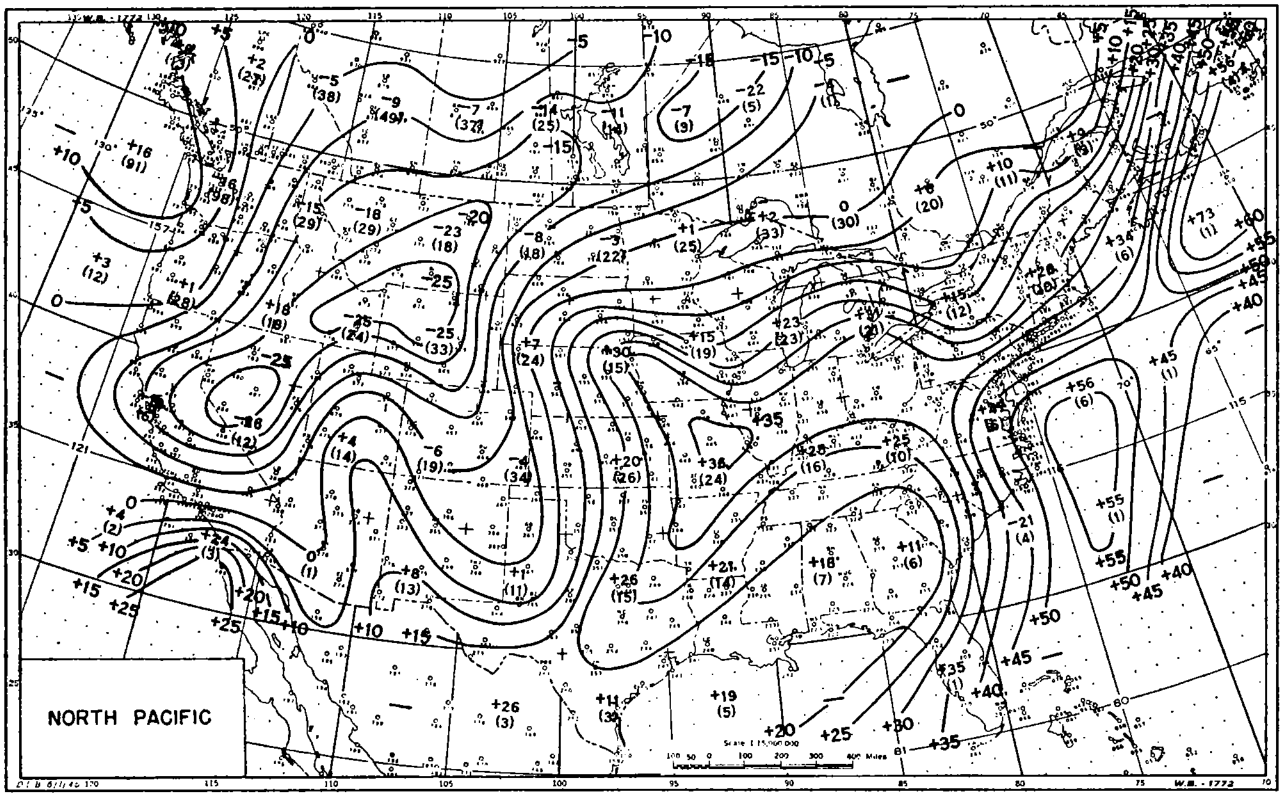

FIGURE 3.—Map showing isograms of average 24-hour direction of movement of winter cyclones, drawn from average direction of movement by 5° squares (shown by numbers), based on winter cases in Bowie and Weightman data (numbers in parentheses).

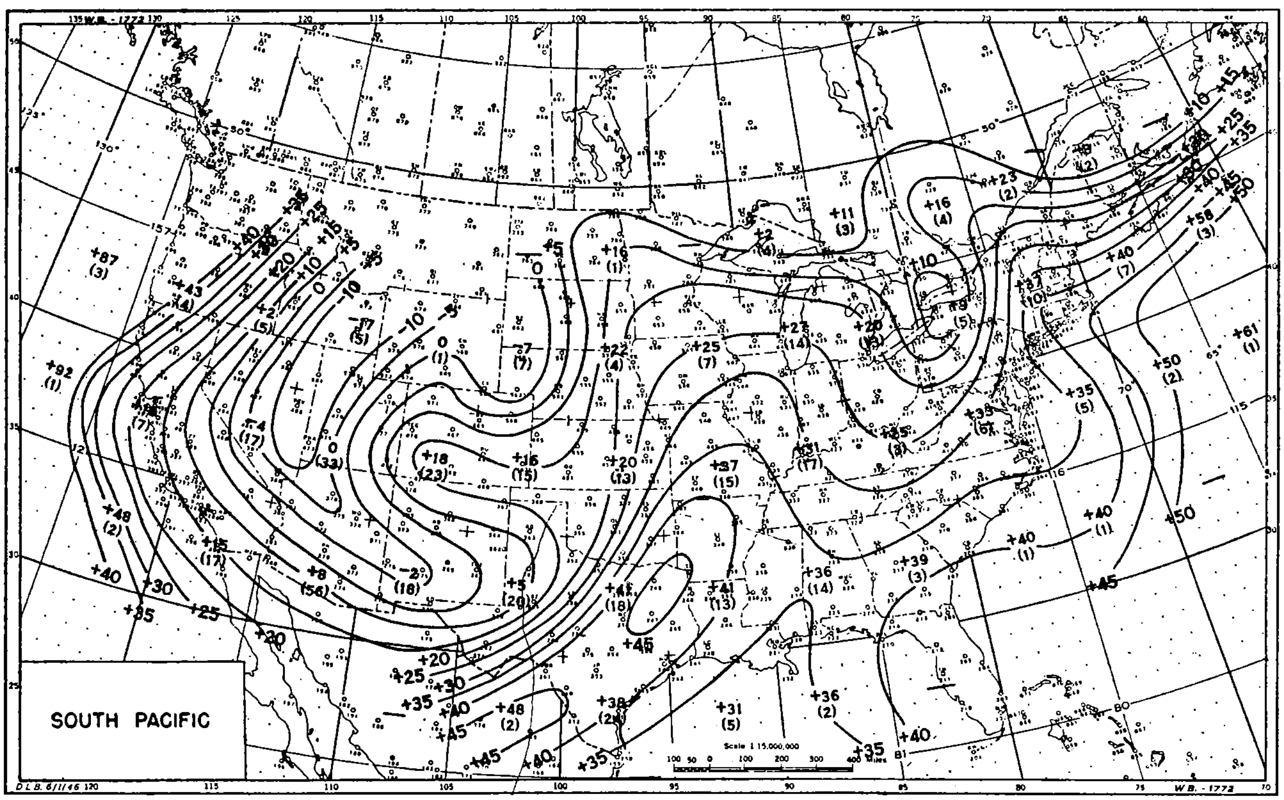

FIGURE 4.—Map showing isograms of average 24-hour direction of movement of winter cyclones, drawn from average direction of movement by 5° squares (shown by numbers), based on winter cases in Bowie and Weightman data (numbers in parentheses).

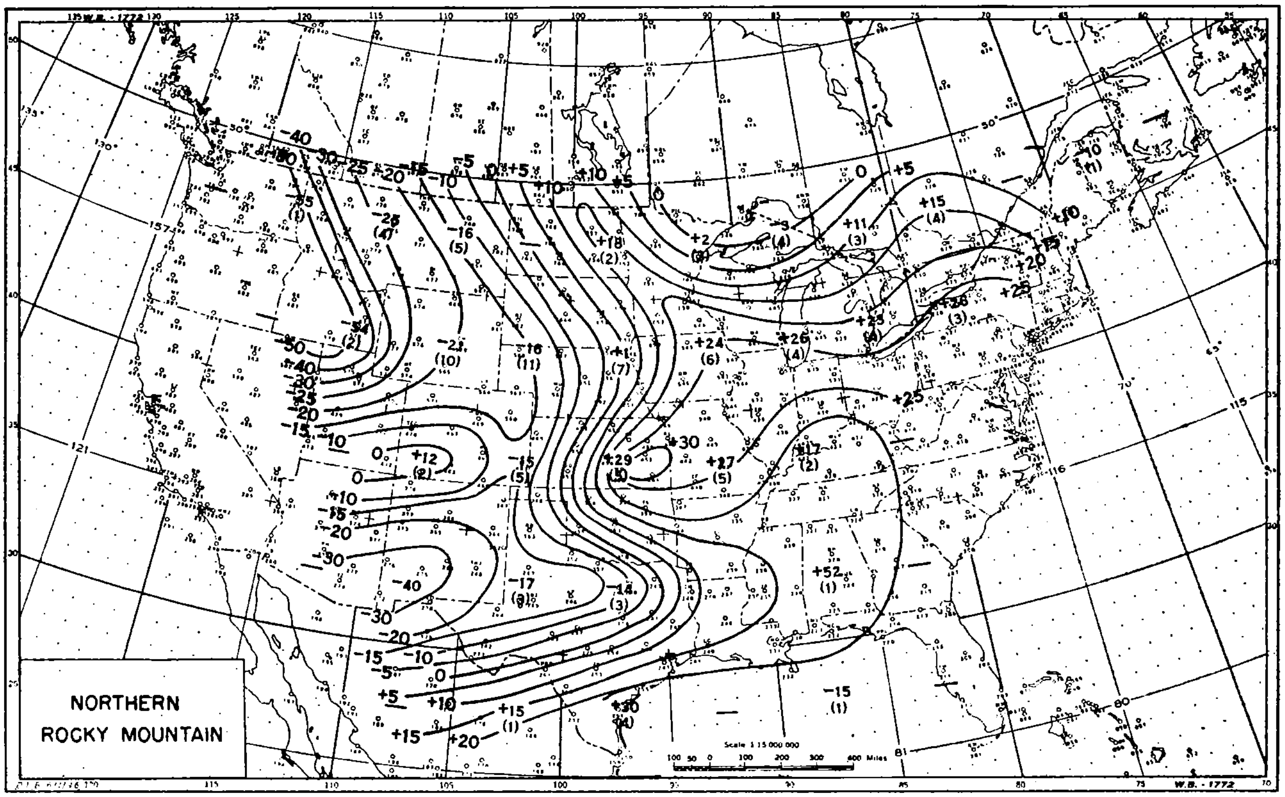

FIGURE 5.—Map showing isograms of average 24-hour direction of movement of winter cyclones, drawn from average direction of movement by 5° squares (shown by numbers), based on winter cases in Bowie and Weightman data (numbers in parentheses).

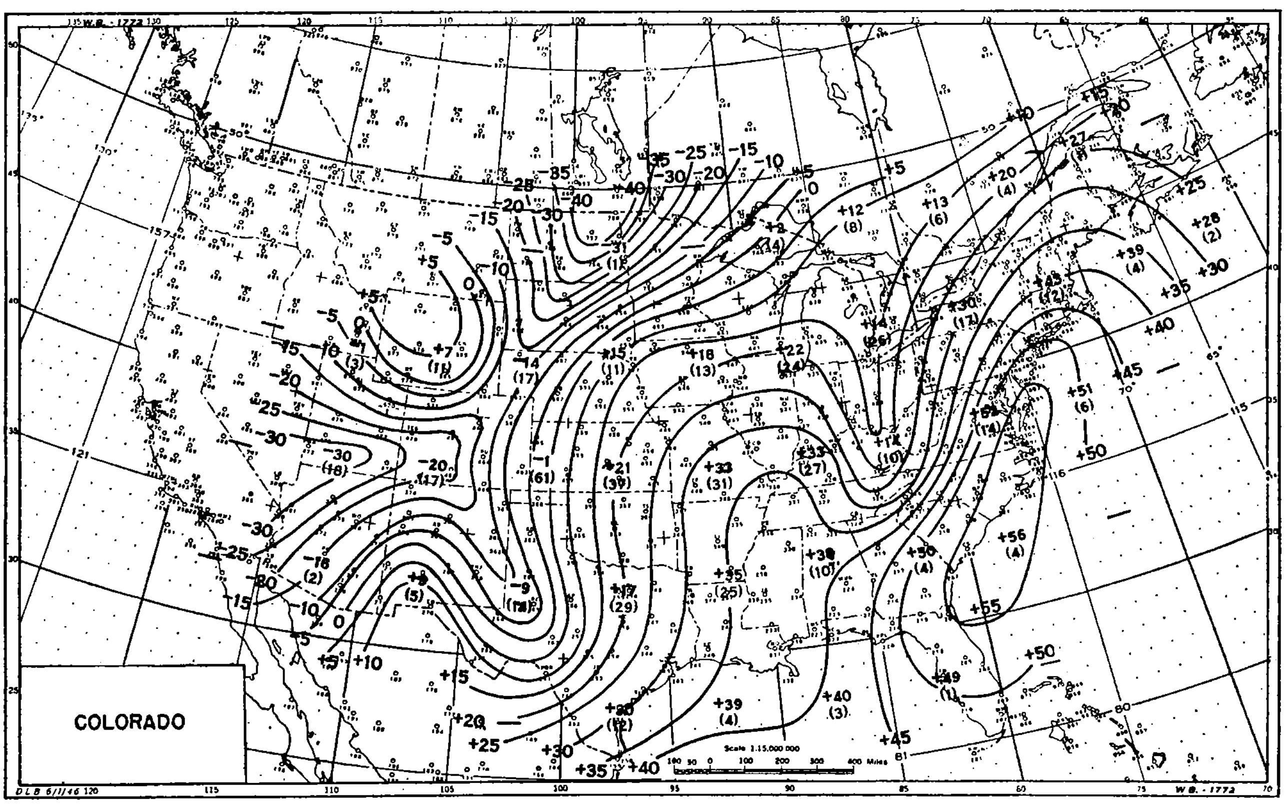

FIGURE 6.—Map showing isograms of average 24-hour direction of movement of winter cyclones, drawn from average direction of movement by 5° squares (shown by numbers), based on winter cases in Bowie and Weightman data (numbers in parentheses).

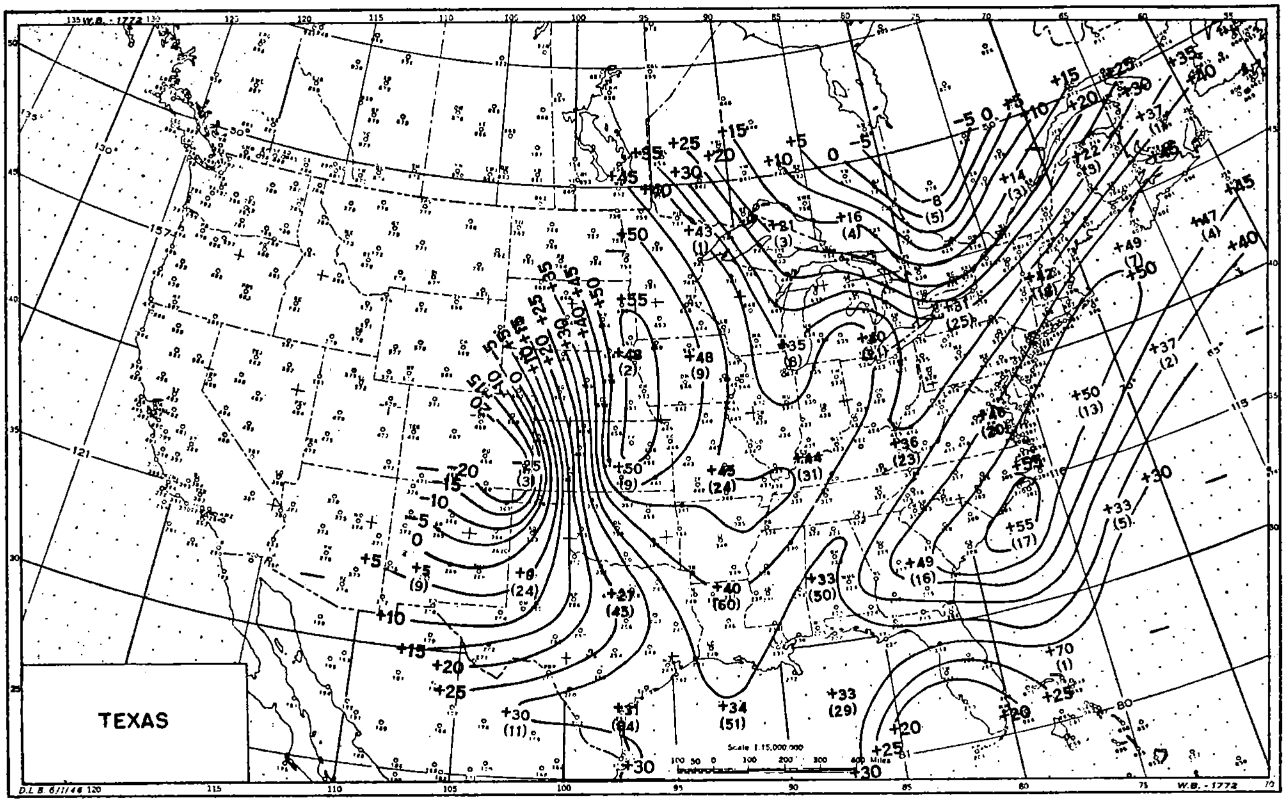

FIGURE 7.—Map showing isograms of average 24-hour direction of movement of winter cyclones, drawn from average direction of movement by 5 °squares (shown by numbers), based on winter cases in Bowie and Weightman data (numbers in parentheses).

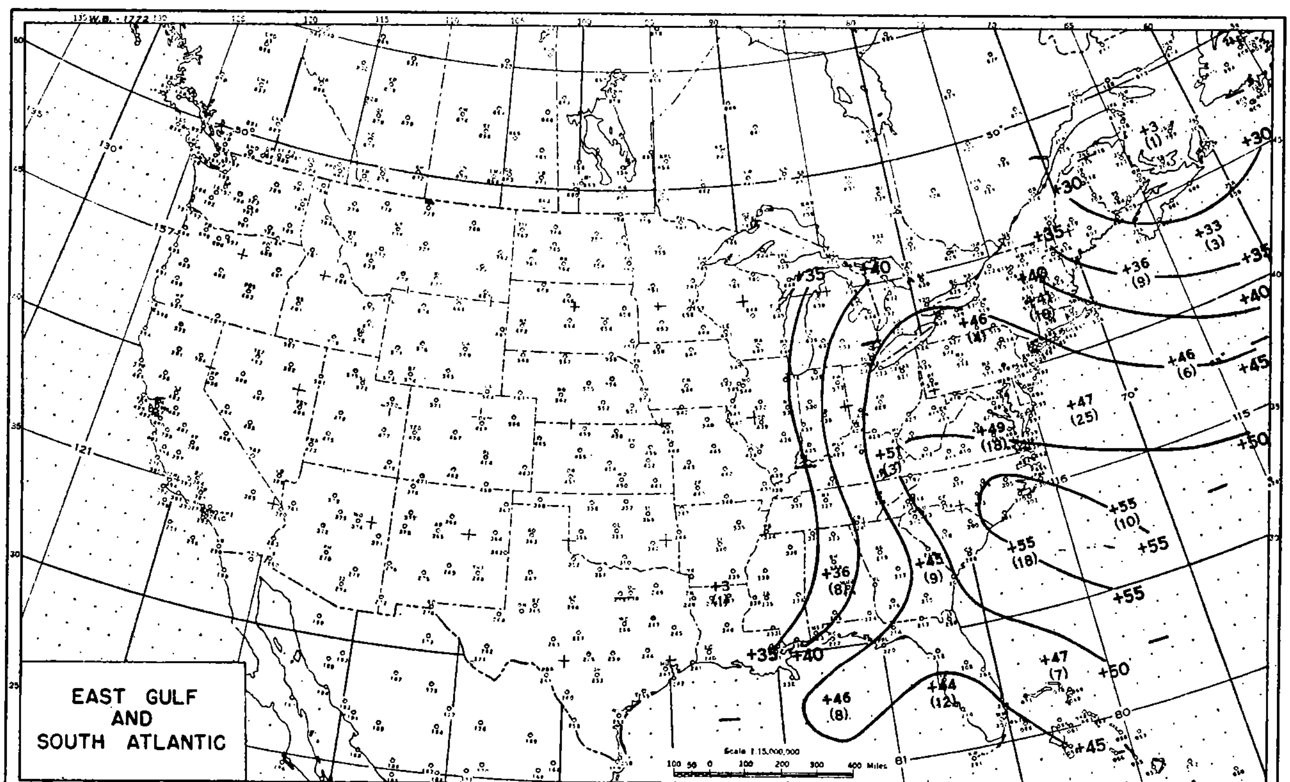

FIGURE 8.—Map showing isograms of average 24-hour direction of movement of winter cyclones, drawn from average direction of movement by 5° squares (shown by numbers), based on number of winter cases in Bowie and Weightman data (numbers in parentheses).

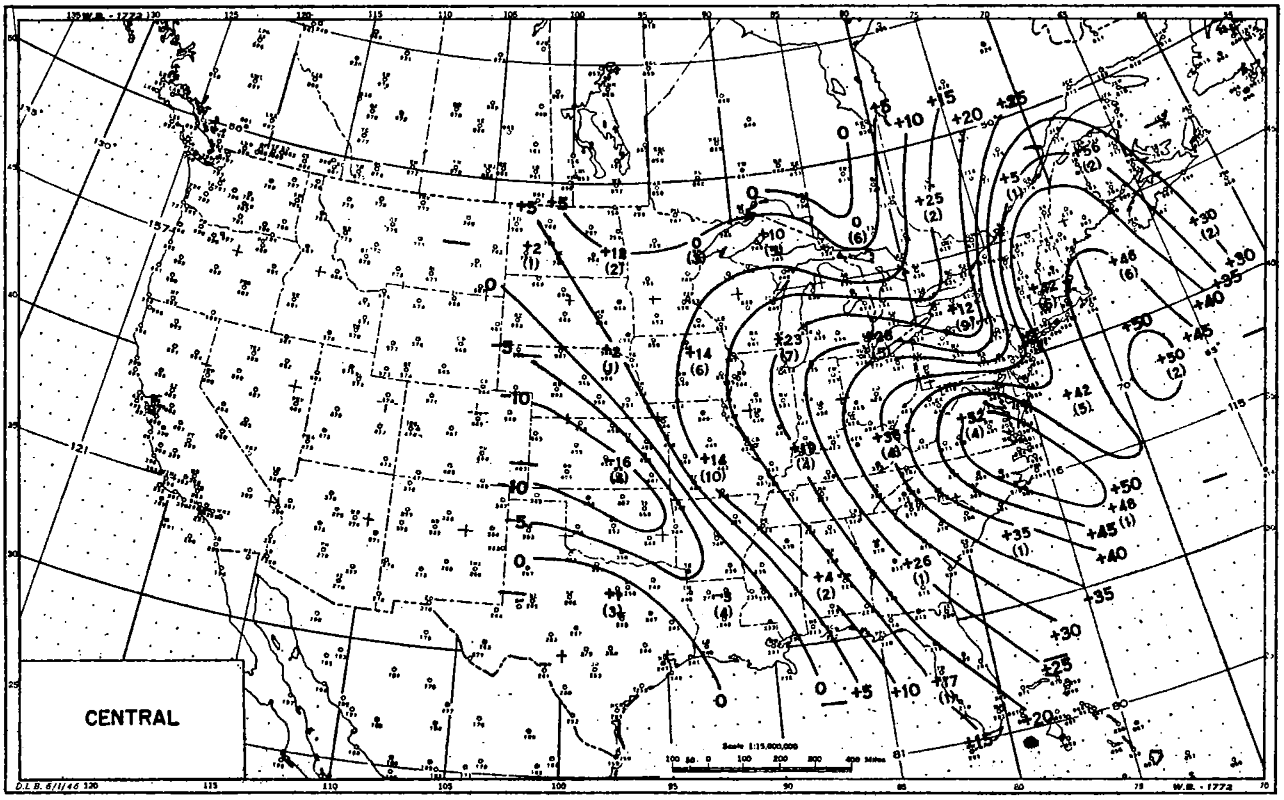

FIGURE 9.—Map showing isograms of average 24-hour direction of movement of winter cyclones, drawn from average direction of movement by 5° squares (shown by numbers), based on number of winter cases in Bowie and Weightman data (numbers in parentheses).

collected from the available weather maps of 1941 through 1945. Only those cases were chosen which conformed to the following conditions: (1) An identifiable low pressure center or wave existed and could be followed for at least 30 hours; (2) the various aspects of the synoptic situation were sufficiently definite that the meteorological factors used in this study could be evaluated with reasonable accuracy. Each low center was first classified according to the area in which it first appeared in figure 1. When it was thus typed, the appropriate normal direction of movement was determined from the correct map of figures 2 through 9. For each low the direction from the current position to the position 30 hours later was measured with an ordinary protractor, as described above. The observed 30-hour direction value obtained in this way is the variable this study aims to forecast; therefore, those observed values are considered as the dependent variables.

The curve in figure 10 was fitted to the data by a simple procedure which combines the method of average points with a graphical technique [2]. The data were divided into groups according to the values of the independent variable (the abscissa), and the mean value of the dependent variable (the ordinate) was computed for each group; these are represented by the crosses on figure 10. The curve shown was drawn by eye to fit what appeared, from the group averages, to be the approximate form and trend of the relationship. This is, of course, not an exact method of determining a relationship, but it can be done quickly and easily, and for all practical purposes it gives what appears to be an adequate answer. (The curves in figs. 11, 12, and 13 were prepared in the same way.) From the curves of figure 10 it is readily apparent that a relationship exists (linear correlation 0.64), but it is also apparent that forecasts based on normal direction alone would be unsatisfactory. Most of the cases with negative normals (i. e., those having a normal direction to the south of east) are Alberta Lows, and although there is little variation in the normals, there is considerable variation in the observed 30-hour direction of movement. Figure 10 shows that normal direction is, in general, a rather pertinent factor in forecasting the future 30-hour direction of movement of lows, but it also illustrates the condition alluded to previously, viz., a factor may be useful in certain ranges of the data but nearly useless in others.

DIRECTION OF MOVEMENT DURING THE PAST 6 HOURS

To many meteorologists the future path of a low is to some extent indicated by its track during the past few hours. Probably a more desirable indication of direction of movement would be the instantaneous direction at the time of the current map, but since that is very difficult to obtain from the weather maps, the straight-line direction from the position of the low center 6 hours past to its current position was used.

Figure 11 shows for the 68 cases described above the relationship between the direction of movement of low centers during the past 6 hours and their observed direction of movement during the subsequent 30 hours. It thus represents an evaluation of extrapolation. The relationship appears to be good enough to be useful for forecasting (linear correlation = 0.74), but the scatter to the left of the zero line suggests that low centers which have not "recurved" toward the north will cause most errors in direction forecasts based on extrapolation. (A "recurved" low is here defined as a low center which had moved to the north of east during the past 6 hours, i. e., the direction of movement during the past 6 hours is positive when measured in accordance with the previously described technique for measuring 30-hour movements.)

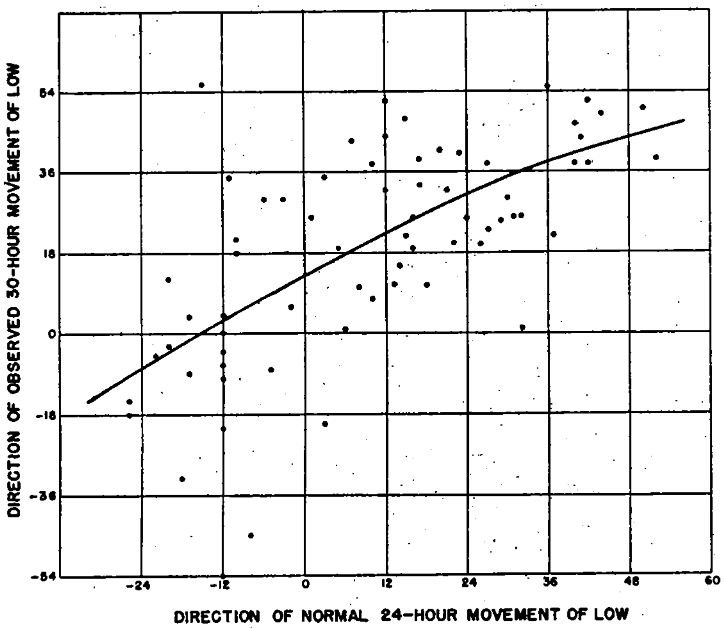

FIGURE 10.—Graph showing relationship between direction of normal 24-hour movement of winter cyclones and the direction of observed 30-hour movement of 68 lows in original data.

ORIENTATION OF THE MAJOR AXIS OF THE TROUGH

Petterssen [3] has suggested that for elongated pressure centers the direction of movement lies between the longest symmetry axis and the isallobaric gradient through the center. Initially, considerable time and effort were expended in this study to evaluate that rule. Various attempts were made to express the effectiveness of the direction of the major axis of a low center as a function of its degree of elongation. Some success was achieved, but the difficulties of measuring the lengths of the major and minor axes made the resultant charts subject to large errors; therefore, all attempts to make use of the degree of elongation were abandoned, and merely the orientation of the large-scale, over-all trough in the surface pressure pattern was used for trough direction and evaluated separately. The direction of elongation of the few innermost isobars of a given low center was discarded in favor of the orientation of the "valley" wherein the low center was found, usually between two or more rather extensive high pressure cells. In some respects, however, this item was rather unsatisfactory to evaluate, since there is sometimes a doubt as to which direction to call the trough direction. For example, with an Alberta Low in Kansas and a definite north-south trough, it would in some ways be no more logical to consider the trough direction as north from the center than south from it. In the majority of cases the direction which agreed closest with the direction of movement during the past 6 hours was chosen, although no exact rules were formulated and each case was considered rather subjectively. In those cases where the trough direction was too indistinct for trustworthy determination, the low center was considered to be circular, and the 3-hour isallobaric gradient (discussed in a later section) was substituted for trough direction. This substitution was somewhat arbitrary, but any device which systematically combines a number of variables into a "forecast" becomes useless if, and when, one of those variables is missing; therefore, any variable used must have some numerical value for each and every case. If in a given case some of these factors cannot be expressed with some degree of accuracy, that case must be considered as one to which the device in question is not applicable—just as extrapolation is not possible for a low that has just formed and has no history.

The trough directions, measured, then, as objectively as possible for the 68 cases, were plotted against subsequent 30-hour directions of movement of the low centers (fig. 12). Results were none too encouraging (linear correlation=0.59), but subsequent work indicated that trough direction seems at times to give indications of storm movement difficult to measure in any other way.

DIRECTION OF THE 3-HOUR ISALLOBARIC GRADIENT [2]

In order to obtain a measure of the average effect of the direction of the gradient in the 3-hour surface isallobars, the direction from the center of the 3-hour anallobaric area to the center of the 3-hour katallobaric area was tabulated for the same 68 observed cases. Of course, these were the anallobaric and katallobaric areas which appeared to be directly associated with the low center—the pressure rise center following the low and the pressure fall center ahead of it.

Figure 13, which shows this measure of the direction of the current isallobaric gradient plotted against the subsequent 30-hour direction of movement of the low center, indicates that the direction from the 3-hour anallobaric center to the 3-hour katallobaric center is a reasonably good first approximation of the direction the low center will move during the next 30 hours (linear correlation=0.72). It was one of the most useful factors found on the current synoptic charts.

Although this measure of direction of the isallobaric gradient was found to be highly correlated with the direction the low center had moved during the past 6 hours (linear correlation = 0.75), it nevertheless seemed to contain some independent information. Relatively high correlations such as this frequently exist among many of the aspects of a synoptic situation. Such correlations between supposedly independent variables add to the complexity of a forecasting problem by making it difficult to find independent measures of a synoptic situation.

COMBINATION OF VARIABLES

STRATIFICATION OF DATA

As the first step in combining the four variables—normal direction, past direction, trough direction, and isallobaric direction—into a single forecast, the data were stratified according to the direction of movement during the past 6 hours. As was pointed out in the previous discussion of that variable, its usefulness was less when applied to cases in which low centers had not recurved than to those which had recurved. Therefore, the 68 cases were stratified into two groups: those in which past 6-hour movement was 0° or in the negative direction (33 nonrecurved cases); and those in which the past 6-hour movement was in the positive direction (35 recurved cases).

[2] The possibility of applying this variable was inferred from the statements of Petterssen [2], and it was used at the specific suggestion of A. K. Showalter, who stated that his experience in forecasting the direction of movement of cyclones had shown the effectiveness of this measure of the field of 3-hour isallobars.

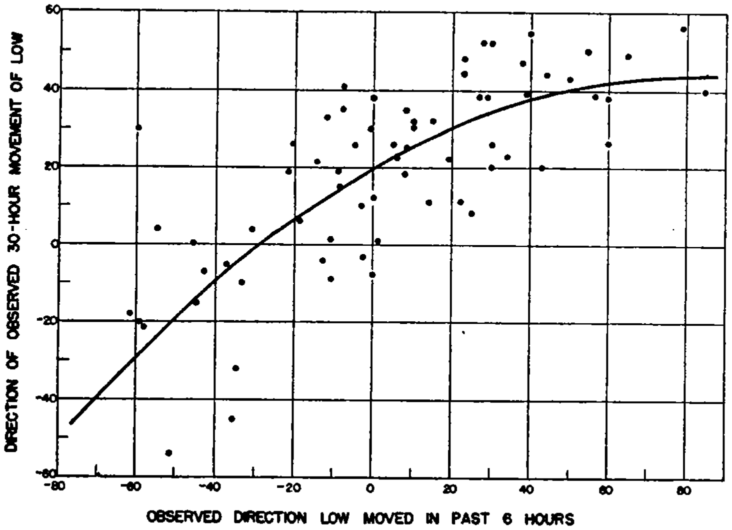

FIGURE 11.—Graph showing relationship between observed direction low moved in last 6 hours and direction of observed 30-hour movement for 68 lows in original data.

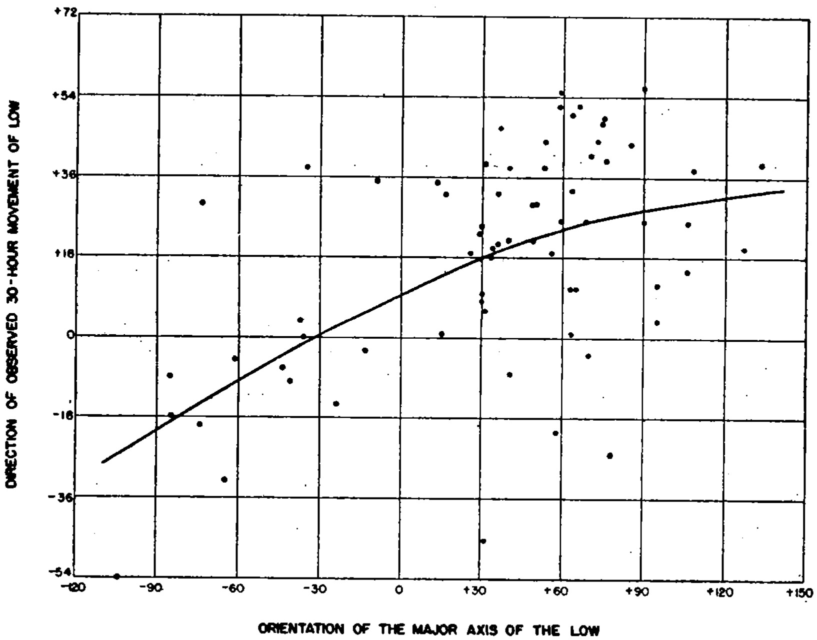

FIGURE 12.—Graph showing relationship between the measured direction of the over-all trough in the pressure pattern and the direction of observed 30-hour movement for 68 lows in original data.

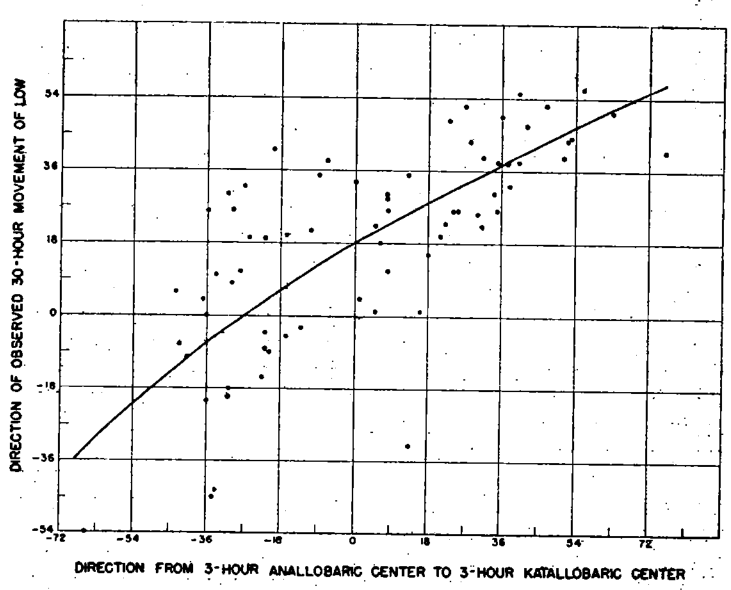

FIGURE 13.—Graph showing relationship between direction from the 3-hour anallobaric center to the 3-hour katallobaric center and the direction of observed 30-hour movement for 68 lows in original data.

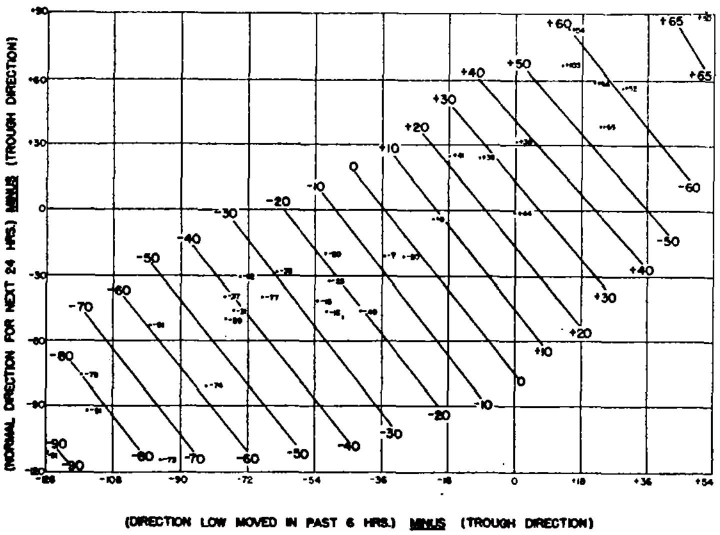

FIGURE 14.—Chart showing data and isopleths in terms of departures of subsequent 30-hour direction of movement of the lows from trough direction, for cases in which the past 6-hour direction of movement of the low center was negative in value. (Data entered beside plotted points are values of direction of subsequent 30-hour movement of low *minus* trough direction.)

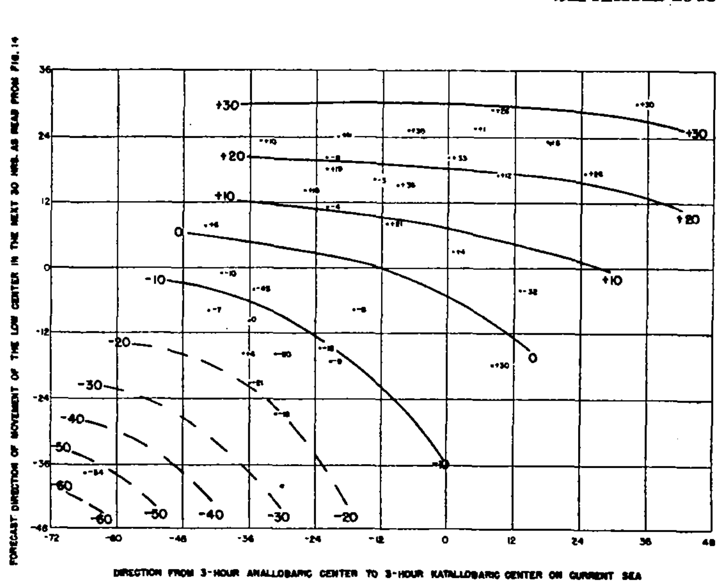

FIGURE 15.—Chart showing isopleths of direction of movement to be forecast for low centers in which the past 6-hour direction of movement was negative in value—with the direction of the 3-hour isallobaric gradient incorporated in the data.

CONSTRUCTION OF CHARTS

Inasmuch as certain aspects of the investigation had indicated that the trough direction was of little or no value in some situations, it seemed expedient to attempt to combine the variables in such a fashion that those situations would automatically be taken care of. Charts in which the data were all in terms of departures from trough direction were therefore prepared on the basis of the working hypothesis that: (1) If the past movement and normal direction for a given low center were both along the trough, the subsequent 30-hour movement might be expected to continue more or less along that trough; (2) if a given low were not moving along the trough at forecast time, it would not likely be guided by that trough during the next 30 hours, and the observed direction would deviate considerably from trough direction.

On the basis of this hypothesis, figure 14 was constructed using the 33 cases of low centers which had not recurved. The abscissa is the value of the past 6-hour direction of the center *minus* trough direction; the ordinate is the value for the 24-hour normal direction of movement of the center *minus* trough direction. The data which were entered beside each point and for which isopleths were drawn are in terms of observed direction of movement of the low center during the next 30 hours *minus* trough direction. A forecast read from the isopleths in figure 14 is therefore in terms of departures from trough direction and must be algebraically added to trough direction in order to obtain the forecast direction with respect to east. Such a forecast will be a function of normal direction, past direction, and trough direction, with trough direction used in a restricted way. This type of graphical correlation uses trough direction in such a way that its coefficient is a function of the coefficients of the other two variables. On the face of it, this might seem undesirable, and the only reason for using trough direction in this way is that this technique for combining the variables produced forecasts which were slightly more accurate than could be made in any other way.

For each point or case in figure 14, "forecasts" were made from the isopleths. They constituted only the first approximation of a forecast, and in order to incorporate the effect of isallobaric direction, figure 15 was constructed. The ordinate is the direction value obtained from figure 14, and the abscissa is the numerical value for the direction from the 3-hour anallobaric center to the 3-hour katallobaric center. Data entered beside each plotted point were values for observed directions of low center movement during the subsequent 30 hours. Isopleths drawn from these data represent direction values in degrees north or south of east. A forecast made from them incorporates the combined effects of (a) where the low center comes from, (b) approximately where it is at forecast time, (c) the direction it has been moving during the past 6 hours, (d) the orientation of the major trough in the sea level pressure pattern, and (e) the orientation of the 3-hour katallobaric center with respect to the 3-hour anallobaric center.

Figures 16 and 17 were constructed in the same manner as figures 14 and 15, using the group of 35 cases in which the direction of movement of the low center during the past 6 hours was positive (recurved classification).

OTHER METHODS OF COMBINING THE VARIABLES

In order to discover whether or not the variables could be combined in a more satisfactory manner, the following methods were used:

(1) All data (68 cases) were treated together graphically, with no stratification.
(2) A series of graphs was constructed using only three of the variables. (Trough direction was omitted, since construction of figures 14 and 15 indicated that it seemed to have little or no effect on the forecast in many cases, although in others it seemed to be significant.)
(3) A linear regression equation was computed for all data:

$$\theta^F_{0+30}=0.28\theta^i+0.31\theta^P+16.0°$$

This equation indicates that the forecast direction for the next 30 hours is 0.28 times the direction from the 3-hour pressure rise area to the 3-hour pressure fall area plus 0.31 times the direction the low center moved during the past 6 hours plus 16°. The value obtained is in degrees from east.

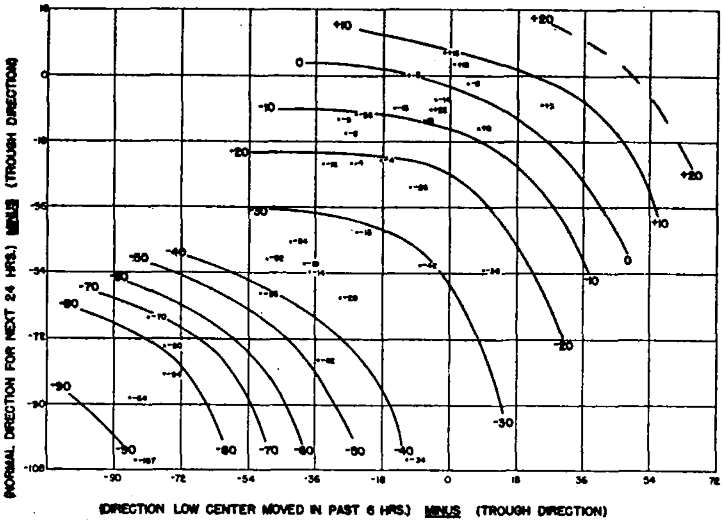

FIGURE 16.—Chart showing data and isopleths in terms of departures of subsequent 30-hour direction of movement of the lows from trough direction, for cases in which the past 6-hour direction of movement of the low center was positive in value. (Data entered beside plotted points are values of subsequent 30-hour movement of low *minus* trough direction.)

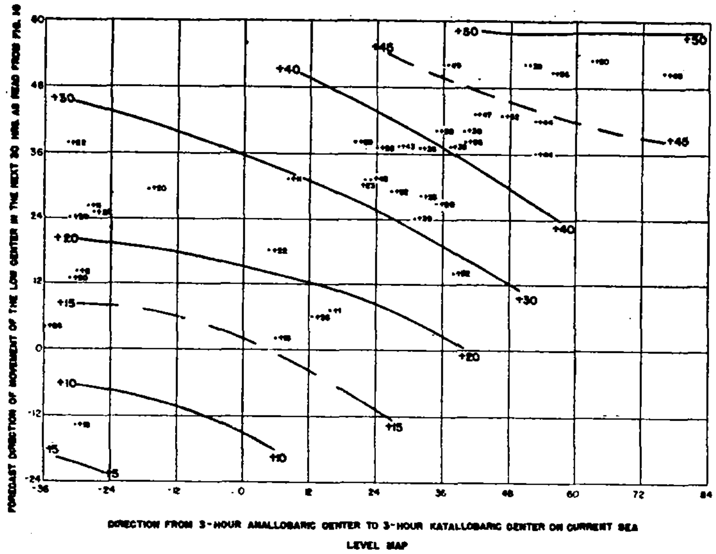

FIGURE 17.—Chart showing isopleths of direction of movement to be forecast for low centers in which the past 6-hour direction of movement was positive in value—with the direction of the 3-hour isallobaric gradient incorporated in the data.

(4) Linear regression equations were computed for the nonrecurved (33) cases, and recurved (35) cases, separately:

Nonrecurved:

$$\theta^F_{0+30}=0.29\theta^T+0.28\theta^P+0.38\theta^N+16.0^\circ,$$

where θ^T is trough direction, and θ^N is normal direction.

Recurved:

$$\theta^F_{0+30}=0.24\theta^i+0.16\theta^P+23.0^\circ,$$

where θ^i and θ^P have the same meanings as in (3) above.

Forecasts made using independent data with each of these systems were, in general, very similar to those made from figures 14, 15, 16, and 17, but none of them appeared to be quite as good as the system embodied in the use of those figures.

TESTS ON INDEPENDENT DATA

Forty-one cases of cyclones from the winters of 1946–47 and 1947–48 were used to independently test the value of figures 14, 15, 16, and 17 as forecasting tools. Direction forecasts were prepared using these charts, which included only the four variables described previously, and were then checked against the observed direction of movement of the low centers. For the sake of comparison, direction values were measured on the prognostic charts prepared by the WBAN Analysis Center for the same 41 cases and checked against observed directions of movement. Resultant errors for each type of forecast were tabulated (see tables 1 and 2).

Table 1 shows the number of the 41 cases tested which resulted in each class error.[3] For example, from the table it can be seen that the Analysis Center prognostications were in error in the amount of −6° to −15° in 9 of the 41 cases; forecasts made from the charts developed in this study, on the other hand, were in error in that amount in 10 cases of the 41 tested. The class interval −5° to +5° contains the cases tested in which the forecasts were "nearly perfect"—deviating from the observed direction by only 5° or less. It should be noted that 17 forecasts (41 percent) prepared by the graphical technique fell into the nearly perfect category.

[3] In the designations of class errors, negative error indicates that the forecast was for movement to the right of the movement which was observed.

TABLE 1.—*Table showing verification of two types of forecasts by indicating distribution of class errors in 41 independent forecasts tested*

Forecasts made by	Class error						
	>−30°	−16° to −30°	−6° to −15°	−5 to +5°	+6° to +15°	+16° to +30°	>+30°
Analysis center	3	3	9	9	10	5	2
Graphical technique	0	3	10	17	3	7	1

TABLE 2.—*Table showing verification data for two types of forecasts for 41 cases tested*

Forecasts made by	Average error	Maximum error	Number of cases with least error	Percent with error >11°
Analysis center	15.8°	−82°	14	54
Graphical technique	10.7°	+39°	26	63

Table 2 shows how verifications of the two types of forecasts compared in other ways. In the first column is the average error (in degrees) made in all cases. The second column indicates the largest error made in any single forecast by each method. The third column demonstrates that, of the 41 cases tested, the Analysis Center prognostications were more nearly correct 14 times and the graphical forecasts were more nearly correct 26 times. (In one instance the error was the same for both methods.) The value in the last column shows the percentage of the time that each type of forecast was within 10° of being correct.

In the light of this verification, the charts apparently perform the task for which they were constructed. Here, then, is a *tested* forecasting tool, and it can be said that forecasts made from these charts will be correct to within 15° about 75 percent of the time, and to within 30° about 98 percent of the time.

Only four simple surface variables have been considered. It is possible that by judicious amendments to this method, based on such considerations as upper air patterns and changes, large-scale temperature patterns, 12-hour pressure changes, and other factors, forecasters may be able to make better direction forecasts; but it is strongly advised that careful count be kept of such amendments. Only by keeping an accurate tabulation of results can the forecaster discover whether or not his amendments are increasing the accuracy of forecasts.

APPENDIX

INTRODUCTION

The purpose of this section is to present what might be called the "negative results" of the study. The first part of the paper has presented factors which were evaluated and finally combined into a forecasting tool; this section presents some of the other variables which were investigated but which either did not improve, or showed no promise of improving, the graphical forecasts based on the four surface variables. Each new variable under investigation was systematically combined with the existing set of graphical forecasts or with the items which went into those forecasts. If this combination led to "more nearly correct" results for the majority of the forecasts, the variable was considered an improvement. As the criterion of the results, "more nearly correct" meant that verification of forecasts made using the additional new variable showed fewer large errors and a smaller mean error for the total number of forecasts.

INVESTIGATIONS

STEERING [4]

The decision to investigate this factor brought with it the problem of method of approach. Little has been written about the term "steering," and its definition varies greatly in use by different forecasters. Among the differences is the variation of opinion of what constitutes the "steering level," with some forecasters believing that the flow pattern at some fixed upper level is the directing influence on the trajectories of surface disturbances, and other forecasters inclining toward choosing, by various means, a different level for each situation. In general it is considered to be some level or combination of levels between 850 and 300 mb., and in the cases of the fixed-level theory, it is believed to be something like the 700-mb. surface or the 500-mb. surface. Differences of opinion are also prevalent concerning the "steering current" at the steering level. Some forecasters look ahead of the closed low existing in the surface circulation and some look behind it for this current; there are those who consider the large-scale broad current in the region of the closed cyclonic circulation and others who consider the flow on only the warm-air side or on the cold-air side to be important. With this diversity of opinion on the concept of steering, it can only be concluded that steering if it is operative, has yet to be explained.

Thus, with established opinion and good physical reasons both lacking for a basis of approaching the investigation of steering in any particular manner, it was decided that the method of attack must be somewhat empirical. The first step was based on a suggestion by Austin [5] that cyclones which are being steered will continue to be steered and vice versa; this seemed a logical starting point in preparing to use the data to indicate when to consider steering as a factor and when to discredit it. In order to test this idea, the procedure finally formulated was to relate the following three factors by a graphical method similar to that of the earlier section of the paper: (a) Departure in direction of past 12-hour movement of the surface low from the direction of orientation of the upper-level contours above it at the beginning of that period; (b) departure of observed subsequent 30-hour direction of movement of the surface low from the orientation of the upper-level contours above it at the beginning of that period; (c) orientation of the upper contours. Both the 500- and 700-mb. levels were used in the plotting, inasmuch as the most satisfactory level for investigation was not known.

Figure 18 is the graph showing the attempt to relate these values of departures from past 12-hour steering to

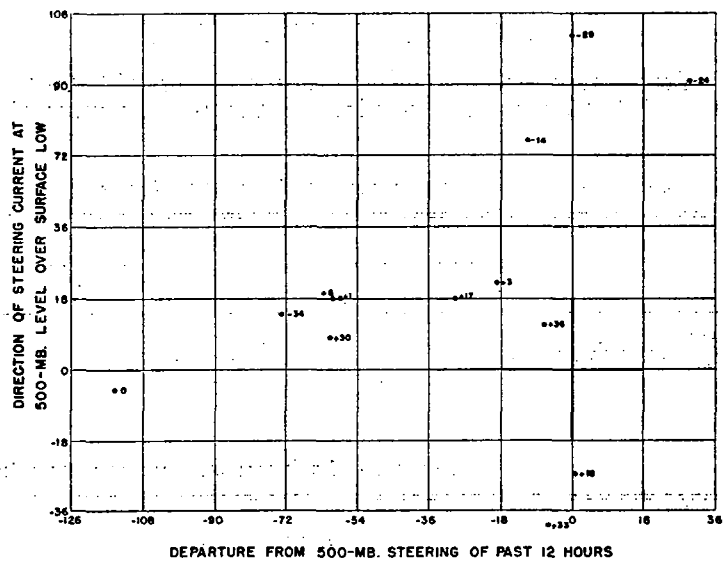

FIGURE 18.—Graph showing attempt to relate values of departures from past 12-hour steering to the departures from steering of the next 30 hours and to the direction of the steering current at 500 mb. directly above the surface low. (Values appearing beside plotted points represent departures from 30-hour steering.)

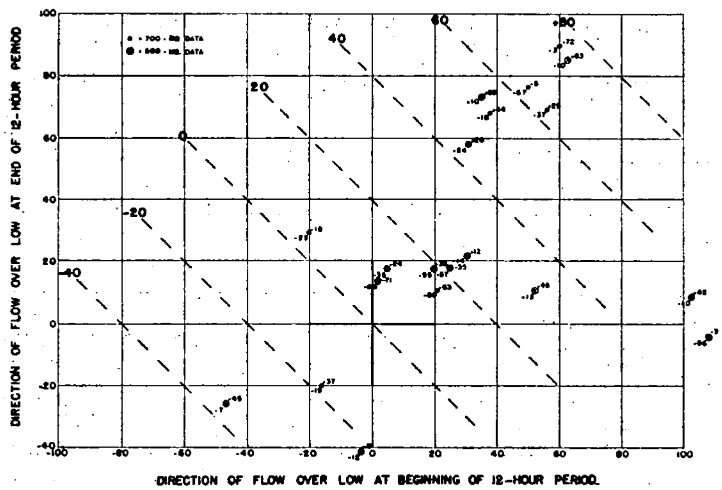

FIGURE 19.—Graph showing direction of 12-hour movement of low center as a function of winds above the low center at the beginning and ending of the 12-hour period. (Data entered above and to the right of plotted points represent values for the 12-hour direction of movement; values below and to the left indicate the difference between the observed direction of movement and the mean direction of flow above the low for the 12-hour period.)

departures from the steering of the next 30 hours and to the direction of the steering current at 500 mb. directly above the surface low. Data entered beside each plotted point are departures from the 30-hour steering. From these, it is apparent that the 30-hour departure value does not seem to be particularly well related to the direction of the 500-mb. steering current, and even less related to the departure from past 12-hour steering. The few plotted data do suggest that lows which followed a steering current at 500 mb. for the past 12 hours (a) continued to follow it during the subsequent 30-hour period when the steering current was directed approximately northeast; (b) departed from 20° to 30° to the right when the steering current was directed to the north; (c) departed 20° to 30° to the left when the steering current was directed toward about east to southeast. A relationship does seem to exist among the three factors, but these few data gave little promise of improving the established graphical forecast technique based on surface parameters only. Even if as many additional cases were plotted on the graph of figure 18 as are now shown, and it were found that for those additional cases 30-hour steering departures were an exact function of past 12-hour steering departures (in itself a very unlikely condition), when they were added to the data already plotted the over-all relationship would still not be particularly good. A graph similar to figure 18 was prepared from 700-mb. data but appeared to be no more promising than this graph from 500-mb. data.

When this first attempt at systematizing the use of steering as a variable had failed, figure 19 was constructed —not as a possible forecasting tool, but as an attempt to find out something about the concurrent relationship between upper-level flow patterns and direction of movement of the surface low center. Only the 12-hour movement of the low center was considered. Figure 19 shows this 12-hour direction of movement as a function of the winds above the low center at the beginning of the period (abscissa) and at the end of the period (ordinate). Data entered above and to the right of each point represent the observed values for the 12-hour direction of movement. The lines drawn sloping upward toward the left represent simply the mean direction of flow above the low during the period, i. e., the arithmetic mean of the ordinate and abscissa at each point. Values below and to the left of each point indicate the difference between the observed direction of movement and the mean direction of flow above the low for the 12-hour period.

It will be noted that these differences, or departures, were negative in the majority of cases, that is, to the right of the steering current. The suggestion of Weiss [6] that departures to the right, such as these, are associated with filling cyclones does not explain the preponderance of these negative values, because, of the 16 lows showing the negative values, 7 filled and 9 deepened. Since no adequate explanation of the preponderance of negative departures was found, the results may be simply a consequence of a biased sample. A check of the individual cases of both 700- and 500-mb. data which were included shows, however, that the cases in figure 19 represent nearly all stages of development of cyclones. Some were deep, cold lows where 700-mb. steering would not have been expected to function but did; others were warm lows with no apparent orographic effects and with uniform flow at 700 mb.—cases in which steering would have been expected to operate but apparently did not; one or two cases seemed to follow very closely the principle outlined by Oliver [7]. Results for the 20 cases were, on the whole, disappointing. For the total number the mean departure from steering was 33°; for the seven 700-mb. cases it was 34°; and for the thirteen 500-mb. cases it was 32°.

These results suggested that forecasts of direction of movement of lows cannot be made satisfactorily by considering only the direction of flow above the surface low center—even if that direction could be known in advance at a number of times during the forecast period. Attention was then directed to another aspect of steering. Since so many different ideas seem to exist concerning *where* to look for the steering current, an attempt was made to use the data to answer that question. The plan was to use the data to establish an "optimum" steering region at some level. The 500-mb. level was chosen for study more or less arbitrarily.

The position of each surface low center was plotted on the 500-mb. chart available at the time that low existed, and a line was drawn from that position (at forecast time) to the observed position of the same low 30 hours later. Then the area around the point marking the position of the current low was inspected in order to locate a region on the 500-mb. chart which would give the correct steering direction for the next 30-hour movement. The direction and distance from the low center to the center of this optimum steering region were recorded for each case. In the polar diagram of figure 20, the distribution of these optimum steering regions is shown with respect to the current position of the surface low centers. From the diagram it is readily apparent that no specific region is the place to look to get the proper steering direction; so the next step in the empirical approach was to try to relate the position of this optimum steering region at 500 mb. to other features of the current synoptic situation.

The distance from the low center to the optimum steering region was not found to be related to (1) direction to steering region, (2) speed of steering current, (3) direction of movement of the surface low center during the past 6 hours, nor to anything else that could be found. Therefore, the mean of all distances was obtained and used. That was about 380 miles from the position of the surface low.

The direction from the low center to the optimum steering region was also plotted against various measures of the current synoptic situation, including those mentioned above. Finally, a somewhat satisfactory geographical distribution was found. (There seemed to be no physical reason why this factor should be related to anything in

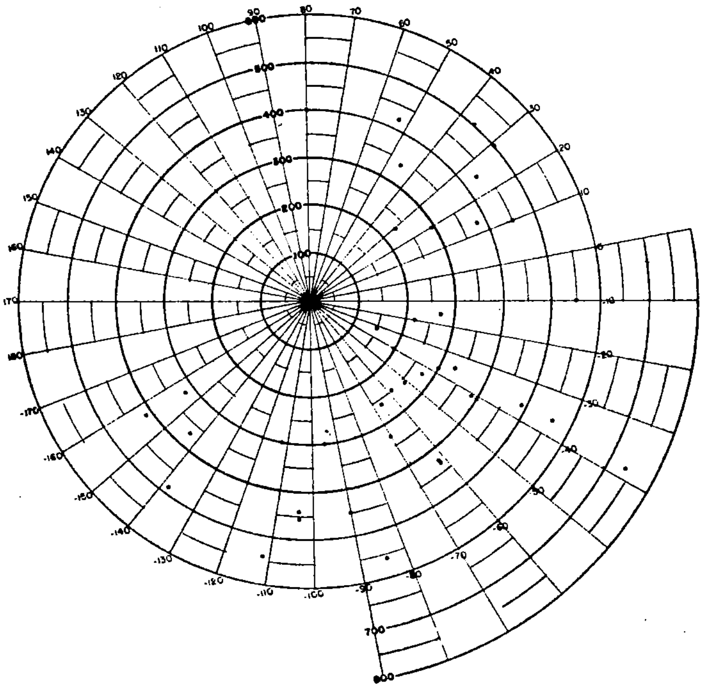

FIGURE 20.—Polar diagram showing distribution of optimum steering regions with respect to current positions of surface low centers.

particular.) The distribution is shown on the map of figure 21, for which the points were located according to the current position of the surface low center. If this relationship is real, it might be explained on the basis that lows in a certain position tend to have a normal direction of movement and *tend* to be accompanied by certain patterns at 500 mb. Therefore, the relationship, if any, may be of a climatological character.

Figure 21 and the mean distance of 380 miles were then used to determine the optimum steering region for the same cases shown in figure 21 plus a few additional cases. The very nature of this process, "working in a circle" and re-using the original data, suggests that good forecasts should be obtained. At any rate, in order to establish a relationship using figure 21 and the distance of 380 miles it was a necessary procedure. When the optimum steering region at 500 mb. was found in this way for each case (many turning out to be the same as originally selected), the direction of the steering current at that indicated optimum point was also measured for each case and was then used as a "forecast direction" for the surface low center movement during the next 30 hours. Figure 22 shows these steering "forecasts" plotted against the observed 30-hour direction of movement of the surface lows. Naturally, a very good relationship resulted—in fact, the best that could be hoped for by using steering as a variable.

The remaining step in this phase of the study of steering was to combine the forecast values obtained in the 53 cases plotted in figure 22 with the forecast values for the same cases as derived from figures 14, 15, 16, and 17 (the graphical technique developed in the first section of the paper). Figure 23 shows these two different forecast values plotted one against the other. Data which were entered beside each point and for which isopleths were drawn are the values for the observed 30-hour direction of movement of the lows. The shape and slope of the isopleths show that, in general, the two forecasts have about equal weight. The average residual from figure 23 is 8.8°, whereas the average residual from figures 15 and 17 is 10.0°. This would appear to be a satisfactory improvement in terms of the forecast, but a test using 22 independent cases indicated that the "progress" was negative.

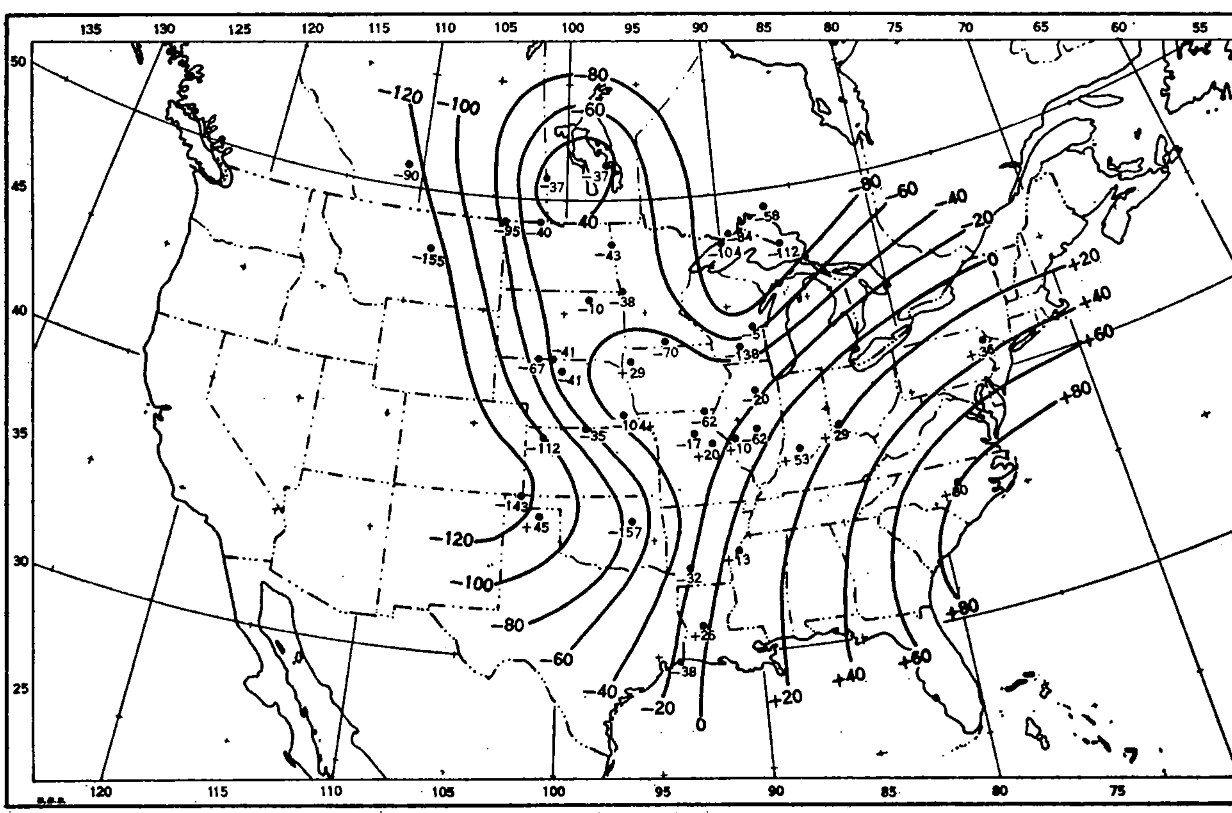

FIGURE 21.—Map showing isopleths representing geographical distribution of directions from surface low center to optimum steering point at 500 mb.

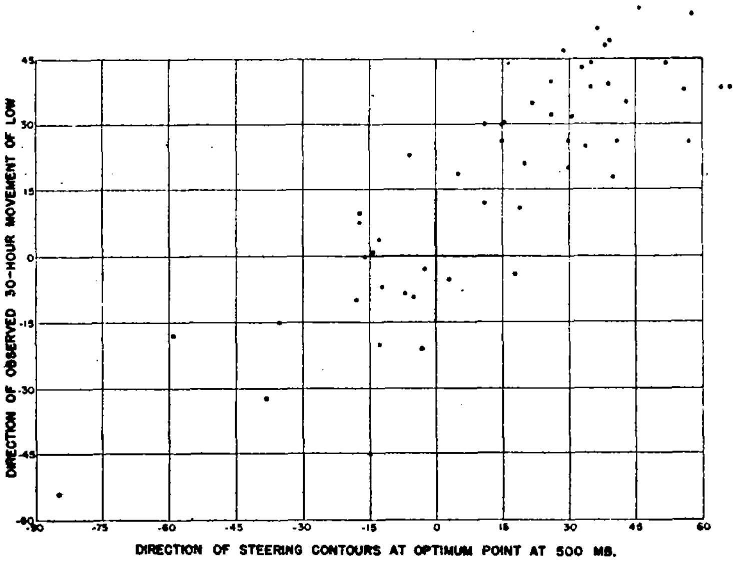

FIGURE 22.—Graph showing direction of steering contours at optimum point at 500 mb. plotted against the observed direction of 30-hour movement of low centers.

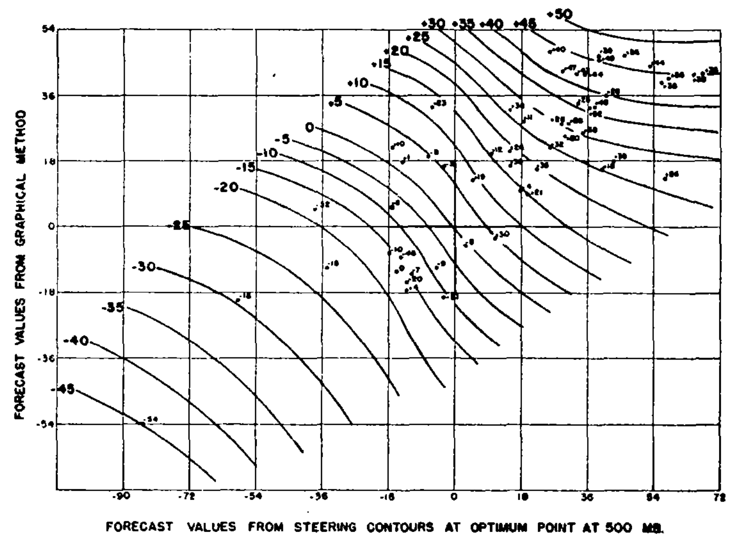

FIGURE 23.—Graph showing 500-mb. "steering" forecasts (from fig. 22) plotted against the forecasts made from graphical technique of figures 14 through 17. (Values appearing beside plotted points represent observed 30-hour direction of movement of the lows.)

This independent test was carried out using 22 of the independent cases that were used to obtain the results shown in figure 18. Figure 21 was used to find the direction from the surface low to the optimum steering region at 500 mb., and the distance of 380 miles was used to determine the exact point. Steering direction was measured at that point. The abscissa of figure 23 was entered with this value and the ordinate entered with the graphical forecast value based on surface data; the forecast direction of movement of the surface low during the next 30 hours was then read from the isopleths on figure 23. The average error for the 22 forecasts thus obtained was 13.5°, whereas the average error for the same 22 cases was only 10.4° when the graphical forecast from surface data was used alone. Of those 22 forecasts, 6 were improved by using 500-mb. steering in addition to surface indications; 3 were not changed; and 13 were made worse. In fact, in any way in which a verification was made, the forecasts had, in general, been made worse by the addition of steering; so the only conclusion that could be drawn was that forecasts made using figures 14 through 17 (based on surface data only) were not improved by using the 500-mb. data in this way.

Various other attempts were made to use steering systematically, but all results were disappointing. One attempt that appeared promising when used on dependent data was the combination of the graphical forecast from surface data and a steering forecast made using the 500-mb. contours 800 miles ahead of the surface low at a point on the line obtained by using the graphical forecast from surface data. However, when tested on independent data, this too failed to improve the original forecasts. Data were also examined in an attempt to justify the practice of many forecasters who use steering as an indicator only when certain conditions hold, such as when the upper winds are stronger than some arbitrary value. However, the data examined did not justify this rule, as steering seemed about the same with strong winds as it did with light winds.

This investigation does not prove that steering at some upper level is not related to the future direction of movement of the surface low center; on the contrary, it proves that a relationship does exist, but it strongly suggests that the relationship is not good enough to improve the forecasts which one can make by systematic use of the four surface factors—namely, normal direction for the next 24 hours, direction of movement of the surface center during the past 6 hours, direction from the 3-hour anallobaric center to the 3-hour katallobaric center, and orientation of the major over-all trough in the sea-level pressure pattern. It is apparently true that the surface low and the upper winds generally move more or less in the same direction, but in many cases the deviation is more than 30°, and any forecast that misses the direction of movement of the low by such an amount is an unsatisfactory forecast if the low moves appreciably. One should conclude, simply from an inspection of figure 19, that such an inadequate concurrent relationship can hardly be expected to improve forecasts when an arbitrary lag of 24 to 30 hours is imposed.

In conclusion, although there are many ways to consider steering that were not investigated, the work done shows rather convincingly that, in general, the forecasts which can be made using the four surface parameters named above cannot be improved by the systematic use of the steering flow at some upper level.

12-HOUR PRESSURE CHANGE AT SEA LEVEL

Many forecasters use the 12-hour pressure change chart to a considerable extent. Precisely how it is used to assist them in forecasting the 30-hour direction of movement of cyclones cannot be stated in a few words, because each forecaster uses it in his own way. In general, however, it may be said that its use involves extrapolating the areas of 12-hour pressure change and superimposing these extrapolated areas on the existing pressure patterns. By any graphical technique such as was used in this study, it is impossible to evaluate exactly the same features which the forecaster uses subjectively; however, it is possible to evaluate certain specific features of the 12-hour pressure change chart.

It was suggested that the direction of movement of the 12-hour katallobaric center during the past 12 hours should be related to the subsequent 30-hour direction of movement of the low center with which it was associated.

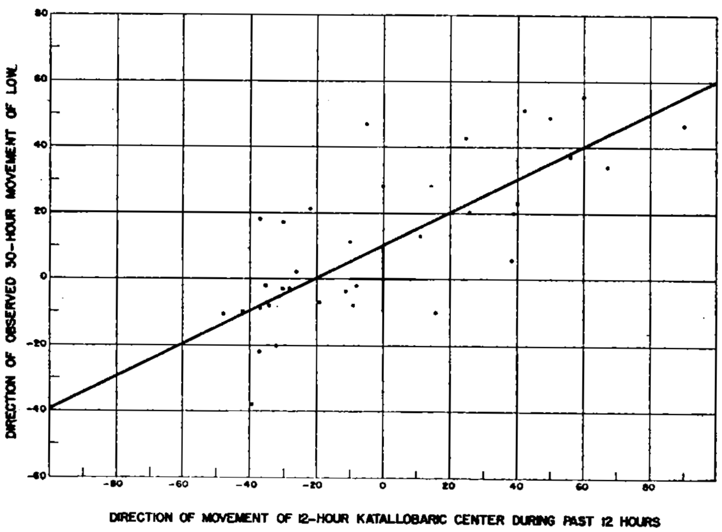

FIGURE 24.—Graph showing relationship of direction of movement of the 12-hour katallobaric center during the past 12 hours with the subsequent 30-hour direction of movement of the low center associated with it.

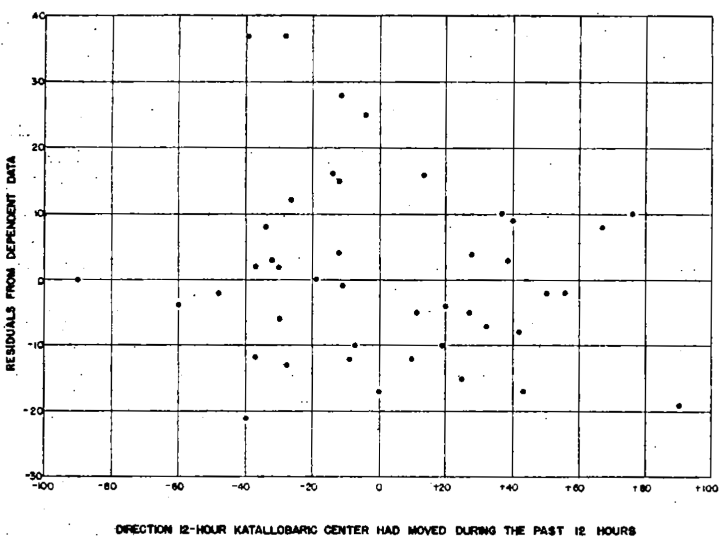

FIGURE 25.—Graph showing relationship between residuals from forecasts made by graphical technique with direction the 12-hour katallobaric center had moved during the past 12 hours.

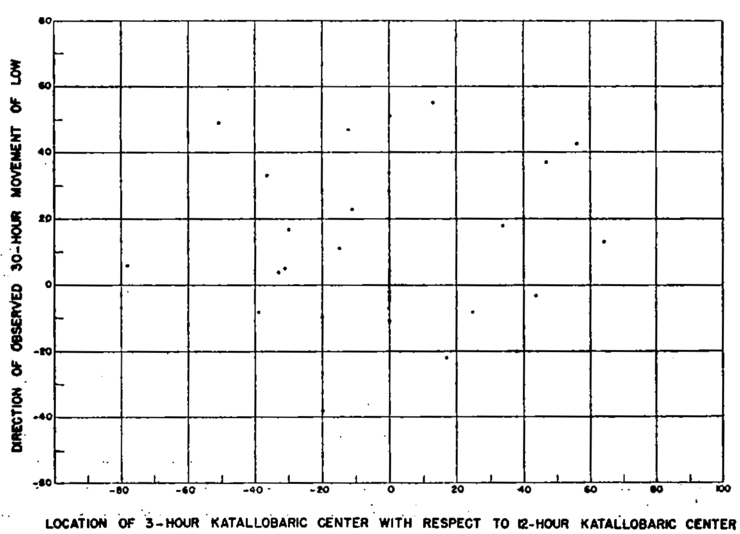

FIGURE 26.—Graph showing relationship between the location of the 3-hour katallobaric center with respect to the 12-hour katallobaric center and the direction of observed 30-hour movement of the low centers.

Figure 24 shows that a relationship does exist and that this means of considering the 12-hour pressure change chart explains approximately one-fourth to one-third of the variability in 30-hour direction of movement.

In order to find out whether or not this measure of the 12-hour pressure change chart would improve the forecasts made from graphs of figures 14 through 17, 43 of the residuals, or errors, from figures 15 and 17 were plotted (fig. 25) against the direction the 12-hour katallobaric center had moved during the past 12 hours. No relationship is apparent from this graph, and a reasonable conclusion is that this simple means of considering the 12-hour pressure change chart would not improve the forecasts prepared systematically from the surface data, mainly because this parameter contains much the same information as do some of the surface parameters.

In another evaluation, figure 26 shows the 30-hour direction of movement of a number of low centers plotted against the location of the 3-hour katallobaric center with respect to the 12-hour katallobaric center. The apparent lack of relationship shown by the graph indicates that the orientation of the 3-hour pressure fall area with respect to the 12-hour pressure fall area is not pertinent information for forecasting 30-hour direction of movement of winter cyclones.

The other aspect of the 12-hour pressure change chart which was tested individually was the direction the 12-hour anallobaric center had moved during the past 12 hours. Figure 27, plotted to test this, shows that probably no significant relationship exists between this factor and the subsequent 30-hour direction of movement of the associated low center.

Since the subsequent direction of movement of the low center seemed to be related to the past movement of the 12-hour katallobaric center (see fig. 24), it seemed logical to surmise that the departure of the subsequent direction of movement of the low from the past 12-hour direction of movement of the 12-hour katallobaric center might be related to (a) the direction the 12-hour anallobaric center had moved during the past 12 hours (ordinate in fig. 28) and/or (b) the orientation of the line between the 12-hour anallobaric center and the 12-hour katallobaric center (abscissa in fig. 28). To find this relationship figure 28 was plotted, with the departure of the direction of subsequent 30-hour movement of the low from the direction of past 12-hour movement of the 12-hour katallobaric center entered beside each plotted point. There does seem to be a tendency for positive departures to be located on the left side of the chart, and vice versa. This indicates that departures are related to the relative orientation of the 12-hour rise and fall areas rather than to past movement of the 12-hour rise area. Therefore, figure 29 was constructed, substituting the past direction of movement of the 12-hour katallobaric center as the ordinate. Data entered beside each case and for which isopleths were drawn are the same as in figure 28. For the 34 cases plotted in figure 29, the average bias is nearly zero. For the same 34 cases, from figures 14 through 17, the average residual was 9.4°. In comparison, 12 of the residuals from figure 29 are 15° or greater, while only 9 of the residuals from figures 14 through 17 are 15° or more.

Even though figure 29 does not appear to fit the data as well as do figures 14 through 17, the possibility existed that some of the errors which were made using the latter figures could be accounted for by the forecast made from figure 29. To test this, figure 30 was plotted, showing the residuals from the graphical forecasts made from dependent surface data plotted against forecasts made from figure 29, i. e., from the 12-hour pressure change

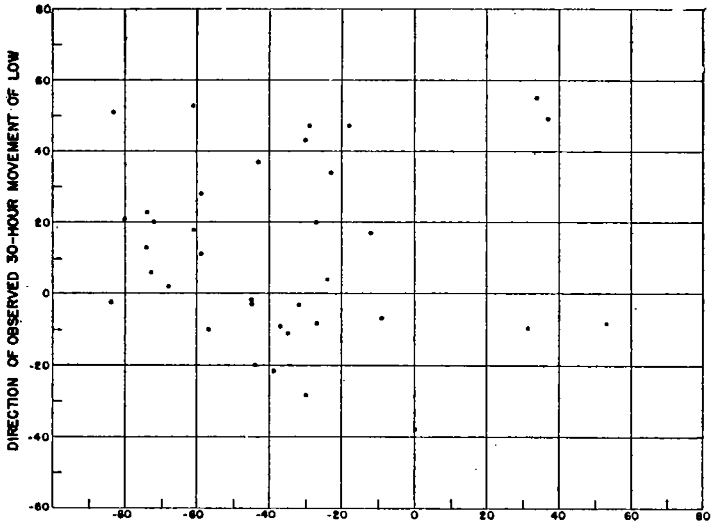

FIGURE 27.—Graph showing relationship between direction of movement of the 12-hour anallobaric center and the direction of observed 30-hour movement of the low center associated with it.

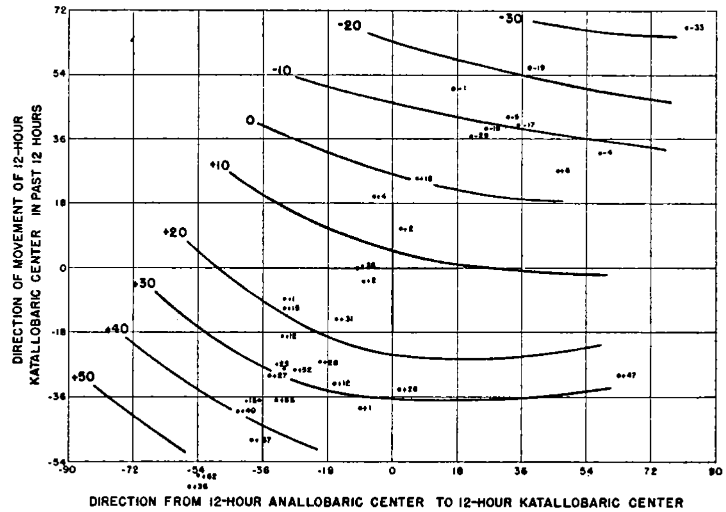

FIGURE 29.—Graph showing departures (data plotted beside each point) of subsequent 30-hour direction of movement of lows from past 12-hour direction of movement of the 12-hour katallobaric center as a function of (a) the direction of past 12-hour movement of the 12-hour katallobaric center, and (b) the orientation of the line between the 12-hour anallobaric center and the 12-hour katallobaric center.

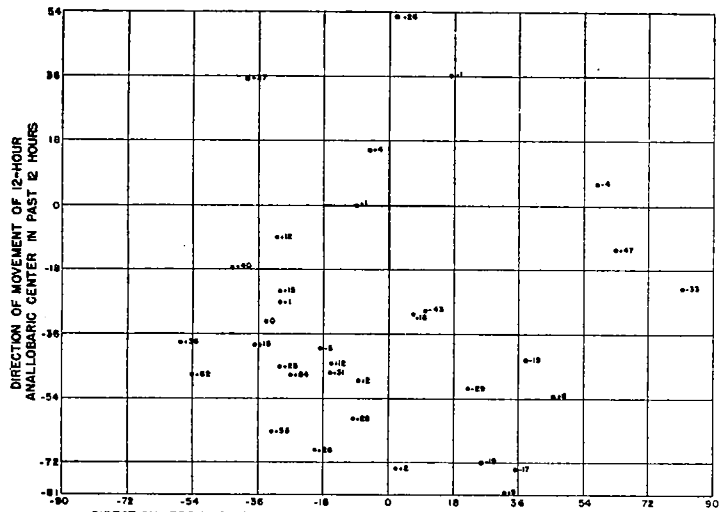

FIGURE 28.—Graph showing departures (data plotted beside each point) of subsequent 30-hour direction of movement of lows from past 12-hour direction of movement of the 12-hour katallobaric center as a function of (a) the direction of past 12-hour movement of the anallobaric center, and (b) the orientation of the line between the 12-hour anallobaric center and the 12-hour katallobaric center.

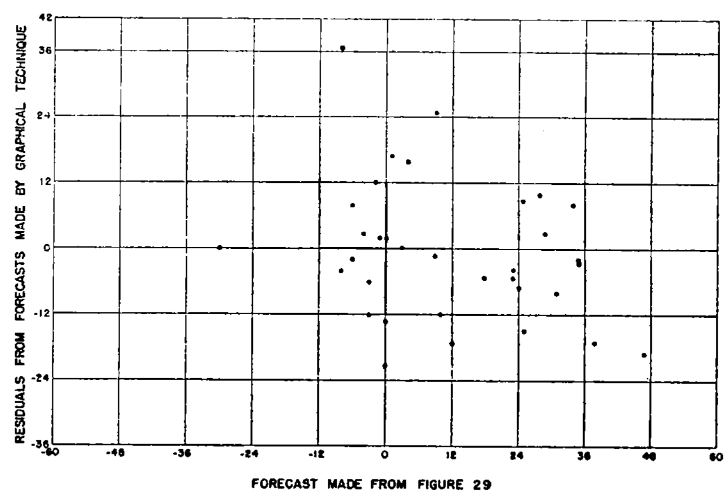

FIGURE 30.—Graph showing residuals from forecasts made from figures 14 through 17 plotted against forecasts made from figure 29.

chart data. No significant regression was apparent, and therefore, the information from the 12-hour pressure change chart was simply a duplication of the information which went into figures 14, 15, 16, and 17, and did not improve the original graphical forecasts. This sort of duplication of information seems to be characteristic of meteorological phenomena; the various aspects of a current synoptic situation are so interrelated that it is possible to get a given answer in many different ways from many different aspects of the situation.

Many other attempts were made to use the 12-hour pressure change chart systematically in forecasting the direction of movement of low centers. Although certain aspects of the chart were found to be related to the subsequent direction of movement of cyclones, no means of improving the graphical forecasts made from surface data were found.

"DOMINANT ANTICYCLONES" AT SEA LEVEL

It frequently appears from an inspection of a series of synoptic surface charts that the movement of a given cyclone is being affected to a considerable extent by the relative position and movement of some nearby anticyclone—an effect referred to as "blocking" in certain types of situations. Considerable effort was made to systematize this seeming effect, but the results were largely negative.

In each case, the "dominant high," or anticyclone, was selected from the map by inspection. Generally one was chosen which was found in some easterly direction from the low center and within approximately 1,000 miles. For experimental purposes, the synoptic situation during the 30-hour forecast period was inspected to find out which high cell had appeared to be most important in the movement of the low, and that high was chosen as the dominant one. It was thought that if the high proved important, the important features might be the direction from the low center to the high center and the direction that the high center was moving at forecast time. (For the latter direction it was generally necessary to measure the direc-

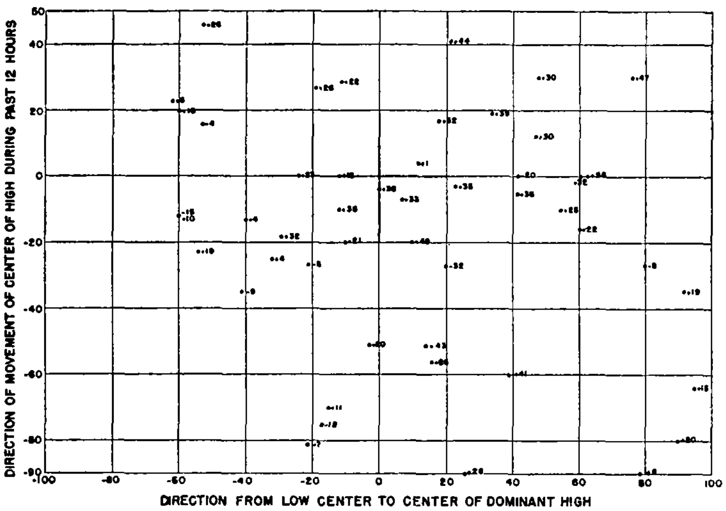

FIGURE 31.—Graph showing relationship of direction low center moved during subsequent 30 hours (values entered beside plotted points) to (a) the direction from the low center to the dominant high, and (b) the direction in which the high center had been moving during the past 12 hours.

tion of movement of the high center over the last 6 or 12 hours.) For example, a low in eastern Kansas might not be expected to move very much north of east during the next 24 to 30 hours if an extensive high cell existed in the vicinity of Winnipeg and were moving more or less southeastward.

Figure 31 shows the direction from the low center to the center of the dominant high plotted against the direction the high center had been moving during the past 12 hours. Data entered beside each point are directions the low centers actually moved during the subsequent 30 hours. The lower right-hand portion of the chart represents the example above, and none of the cases therein actually moved to the north of east-northeast. The upper right-hand portion of figure 31 represents cases in which the high was to the northeast and was moving more or less toward the northeast. In such cases the low tends to follow along behind the high as it moves out. From many aspects this chart appears to be reasonable and to be somewhat in agreement with synoptic experience, but too many cases do not fit. If a logical pattern could be drawn, it would be an extremely complicated one with regions of more or less discontinuity in it.

Charts similar to figure 31 were constructed with the residuals from figures 14, 15, 16, and 17 entered beside each plotted point. For all cases together, no relationship was apparent; but when the cases were stratified according to geographical types, the residuals from forecasts for the Alberta Lows seemed to be systematically distributed. However, when tested on independent data the relationship was almost completely reversed, so the idea of improving the graphical forecasts by using the dominant high was abandoned.

THICKNESS OF THE LAYER FROM 1,000 TO 700 MB.

It has been suggested that cyclones tend to follow closely along the line which represents the thickness of the layer from 1,000 to 700 mb. above the surface low center. A subjective examination of the data indicated that this was generally true, but no lag relationship could be found. To use this parameter, it would be necessary to forecast first the subsequent position of the thickness line in question before it could be applied to forecasting 30-hour direction of movement of cyclones. This appeared to be a problem which was at least as difficult as forecasting the direction of the low center itself; so after a considerable amount of experimenting with some empirical methods of using the thickness chart, that too was abandoned.

24-HOUR HEIGHT CHANGES AT 500 MB.

It has been suggested by Schmidt [8] and by others [9] that surface lows tend to move in 24 hours into the region currently occupied by the positive 24-hour height change area at 500 mb. An investigation of the data disclosed that this rule must often be applied rather subjectively and even then it often fails.

The sample of dependent data which was used throughout this study included only 3 months for which 500-mb., 24-hour height change charts were available; so it was not possible to make exhaustive tests. The rule proved, however, to be correct within 15° in 8 of the 15 cases tested. Examination of these 15 cases showed that this 500-mb. indication was usually quite different from the indication obtained from the graphical forecast using surface data and that possibly it contained independent information. Figure 32 shows the differences between the graphical forecast and the observed 30-hour directions plotted against the differences between the graphical forecasts and the directions to the 24-hour positive height change area at 500 mb. Apparently a relationship exists between these parameters which could be utilized for a slight improvement in graphical forecasts. However, in 9 out of 10 independent cases used in testing, an exactly opposite relationship was suggested; therefore, it was concluded that both original and test samples were too small and it is very likely that no relationship exists.

GEOGRAPHICAL DISTRIBUTION OF RESIDUALS

It would seem that perhaps this graphical procedure which considers all cases more or less regardless of geographical type and location would tend to produce errors of a certain sign in certain areas. Therefore, figure 33 was prepared to show each case plotted at the position where the surface low center existed at the time the forecast was made. Beside each point the residual from forecasts made from figures 14, 15, 16, and 17 was entered. (Positive values indicate that the isopleths on the charts forecast a direction which was to the north of the observed direction.) Although isograms were drawn on figure 33,

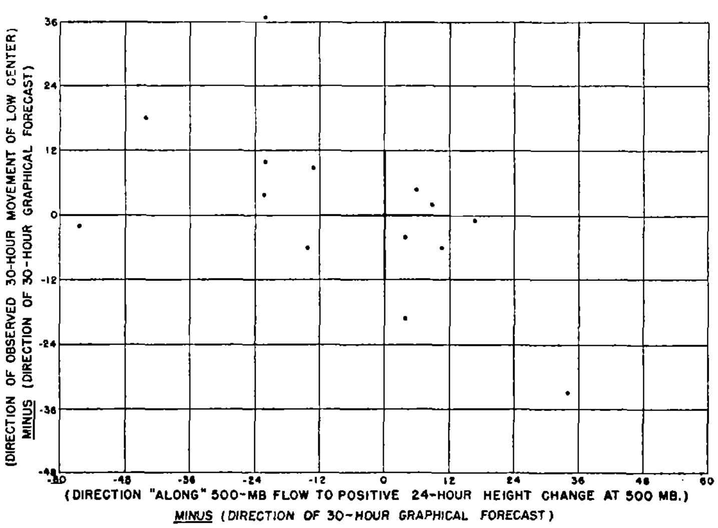

FIGURE 32.—Graph showing differences between the graphical forecasts and the observed directions of movement of the low centers plotted against the differences between the graphical forecasts and the direction to the 24-hour positive height change area at 500 mb.

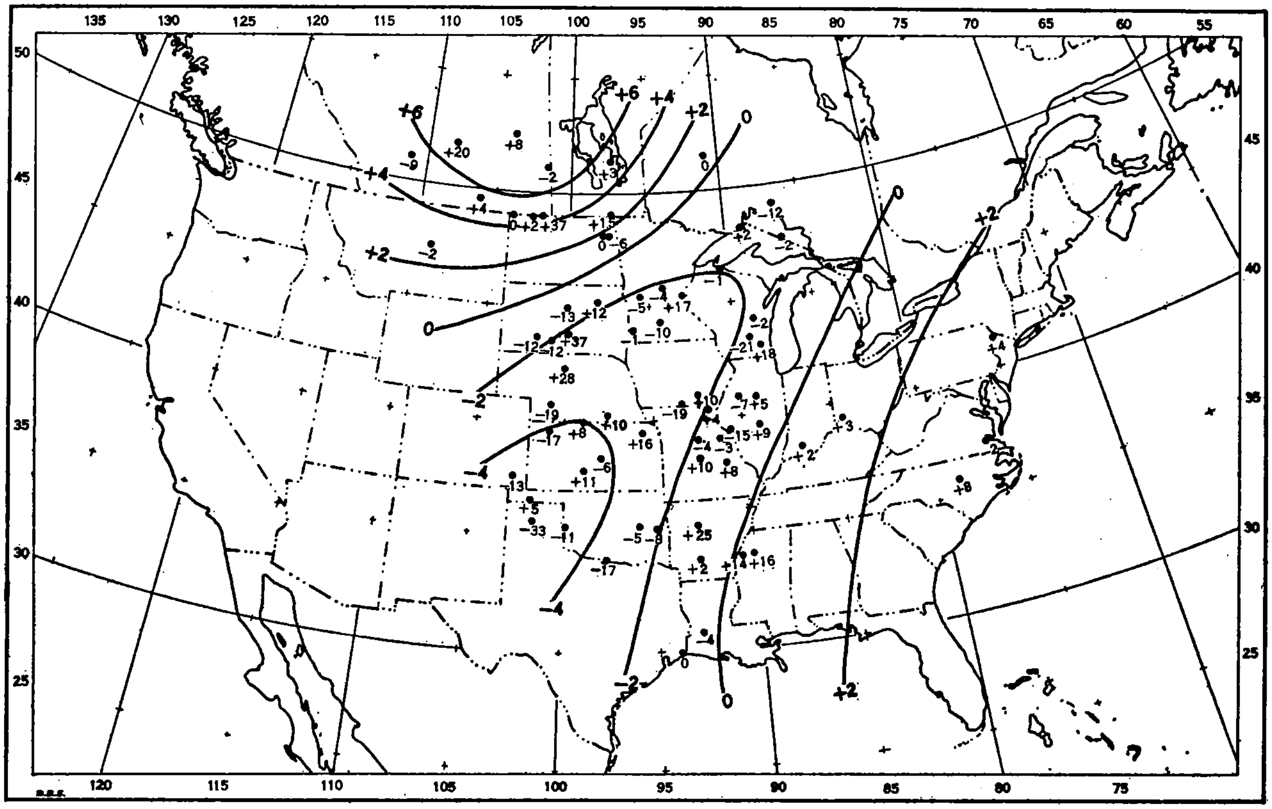

FIGURE 33.—Map showing a plot of each of the 68 cases of dependent data in its geographical location at the time the forecast was made. Isopleths are drawn from values entered beside each point which represent residuals from forecasts made from figures 14 through 17.

there was considerable doubt as to their validity. When the chart was used to determine "expected error" for 27 independent cases, 10 cases were improved, 11 cases were made worse, and 6 cases were not changed. This suggested that no conclusions can be drawn as to the probable amount and sign of the forecasting error due simply to the location of the low in question.

RESIDUALS AND THE SIGNIFICANT VARIABLES

In order to determine whether or not each of the four variables in figures 14, 15, 16, and 17 was used as well as was practicable, the residuals from these charts were plotted against each of the four variables separately. Figure 34 shows the residuals from the 68 cases of dependent data plotted against the direction the surface low center had moved during the past 6 hours. No significant regression is apparent, but it should be noted that all errors of 20° or more occurred when the direction of movement during the past 6 hours had been toward the east or to the south of east, even though the majority of such cases were forecast correctly to within about ±12°. In using the system, therefore, the forecaster should be particularly careful when making forecasts for lows which have not recurved.

Figure 35 shows the residuals from the same 68 cases plotted against the normal direction. No relationship is apparent, but it can be seen that the large errors occurred with cases having negative normals. Nearly all cases to the left of the vertical zero line on Figure 35 are cases of Alberta Lows, and although most are forecast fairly well, some are complete "busts."

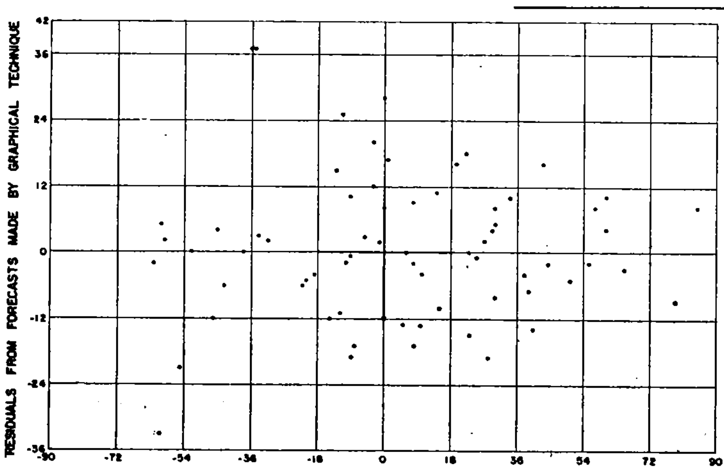

FIGURE 34.—Graph showing residuals from forecasts made by use of graphical technique plotted against the direction the surface low center had moved during the past 6 hours for the 68 cases of dependent data.

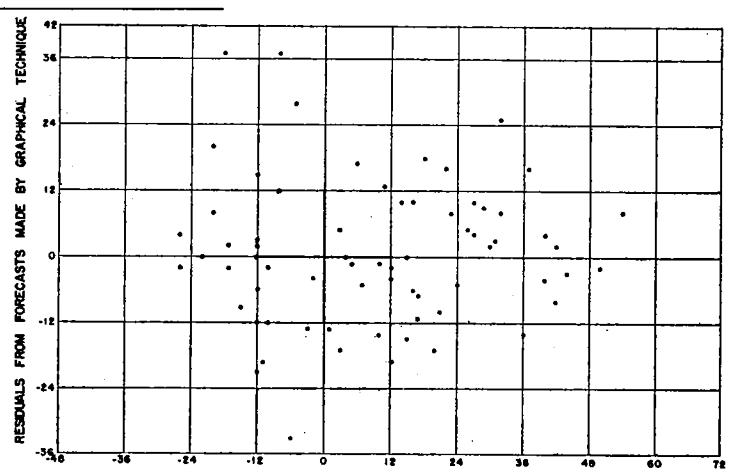

FIGURE 35.—Graph showing residuals from forecasts made by use of graphical technique plotted against the direction of normal 24-hour movement of low centers for 68 cases of dependent data.

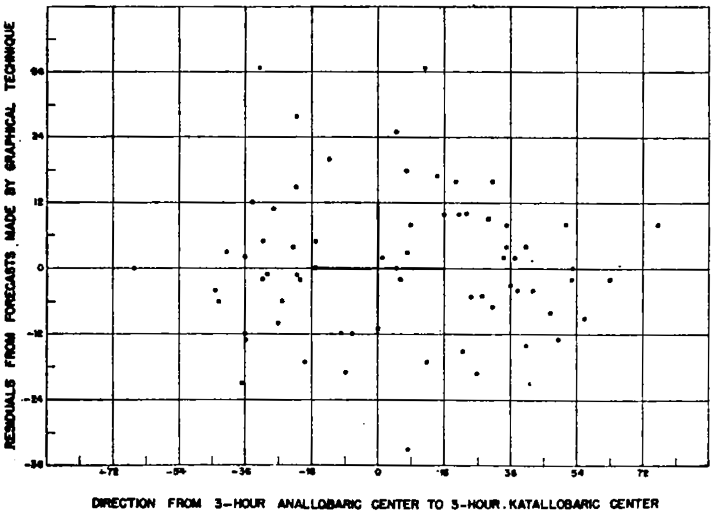

FIGURE 36.—Graph showing residuals from forecasts made by use of graphical technique plotted against the direction from the 3-hour anallobaric center to the 3-hour katallobaric center for the 68 cases of dependent data.

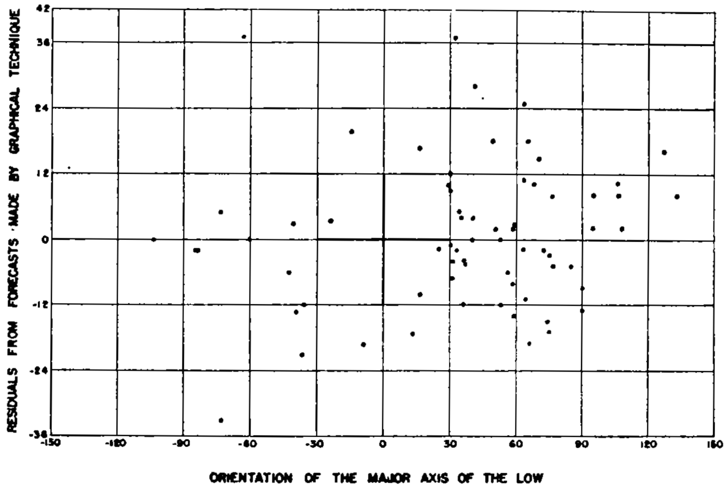

FIGURE 37.—Graph showing residuals from forecasts made by use of graphical technique plotted against the orientation of the major axis of the low for the 68 cases of dependent data.

Figure 36 shows the same residuals plotted against the direction from the 3-hour anallobaric center behind the surface low to the 3-hour katallobaric center ahead of it. Again no relationship is apparent. The large errors seem to have occurred when the isallobaric direction was between 18° and −36°, but since a large part of the cases lies in that range, this is not particularly useful information.

Figure 37 is a diagram showing the residuals as a function of the orientation of the major over-all trough in the sea-level pressure pattern. No relationship exists, and little, if anything, can be said as to the likelihood of occurrence of large errors with any particular range of values of trough direction.

In conclusion, it may be said that the four surface factors which were used to construct figures 14, 15, 16, and 17 were used in such a way that additional information cannot be readily obtained from them.

SUGGESTIONS

This study has brought to light five "unusual" cases, for which complete case studies should be made. Four of them were unusual inasmuch as the forecast results prepared by the system comprised in figures 14, 15, 16, and 17 were in error in positive amounts of 25° or more—that is, the direction forecast was more than 24° to the left of the observed direction of movement of the lows. The fifth case was unusual because the low center actually moved 33° to the right of the forecast direction. "Unusual" is defined in this way to differentiate from the frequent use of the term in connection with cases in which the resultant direction, amount of deepening, speed of movement, or some other particular weather factor is itself unusual. Use of the term in the latter manner is often misleading, because as far as the forecast is concerned, there may be nothing unusual about such a case—the observed movement actually being close to what would have been forecast from a systematic consideration of the current synoptic situation. The unusual case more often turns out to be not the one in which the low center deepened 30 mb. in 24 hours, but the one in which the low center deepened 6 mb. in 24 hours when, from all indications, it should have filled about 20 mb.

The dates and locations of the unusual cases in this study are as follows. As stated above, the first four cases are those which were in error in positive amounts of 25° or more; the fifth is the case which was in error in the negative amount of 33°.

1. A Colorado Low near Little Rock Ark., at 0030 Z. on January 27, 1942.
2. A Colorado Low near Valentine, Nebr., at 0630 Z. on January 6, 1943.
3. An Alberta Low near Valentine, Nebr., at 1830 Z. on January 15, 1943.
4. An Alberta Low near Williston, N. Dak., at 0630 Z. on January 13, 1945.
5. A Northern Rocky Mountain Low near Amarillo, Tex., at 0630 Z. on December 24, 1945.

Presumably the clue to the correct forecast in these five cases does not lie in such simple things as a steering current or a map of sea-level pressure changes. The answer may not be on any of the synoptic charts at all, but, on the other hand, it probably is. Some of the unpublished aspects of this study suggest that the answer lies somewhere in the temperature field.

From an insufficient study of these five cases, it appears that the forecast is likely to be for movement too far to the left when an extensive high pressure area at sea level lies to the north or northeast of the low center and is bringing cold air rapidly southward into the region along the forecast path of the low center. This reasoning, however, does not appear to hold in the case of the low center at Little Rock.

CONCLUSIONS

The graphical device developed in this study for forecasting the 30-hour direction of movement of winter cyclones in the region to the east of the Continental Divide has been used, when applicable, in the routine of the WBAN Analysis Center in the preparation of their 30-hour prognostic sea-level pressure charts since it was made available to them last winter. Forecasters there seem to have found it a valuable tool for assisting them in the preparation of the prognostic chart.

In the course of this study, about 25 or 30 different factors were investigated in an attempt to find items which were related to the subsequent direction of movement of cyclones. Obviously the entire investigation has not been described in this report, but the author will be glad to supply any information possible to those who may wish to communicate with him on phases of the problem which seem to have been overlooked.

ACKNOWLEDGMENT

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